THE IMPACT OF HOLE CLEANING ON RATE OF PENETRATION

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

PETROLEUM ENGINEERING

December 2017

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

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DEDICATION

I am really glad to present my thesis to all who appreciate efforts by people who seek knowledge, since knowledge breeds success in serving all human society by making our life the best area.

ACKNOWLEDGMENTS

I am so much grateful to all who helped me complete my thesis work. At this moment I really would like to appreciate my father who always was encouraging and supporting me in all my life. He was always beside me till his last moment in his life. I will be unable to express my thanks to my family who really stood always beside me and let me feel that I am not letting them alone since I was spending more time in my thesis work. On behave of my family and I, we are grateful to extend the full thank to my thesis advisor and thesis committee Prof. Dr. Abdulaziz Al-Majed, Dr. Mohamed Mahmoud and Dr. Abeeb Awotunde for their usual support, cooperation and the outstanding accomplishment of my thesis. Finally, special thanks to the drilling superintendent of drilling operations of the offshore fields Mr. Eno Eton Omini for allowing me to apply the hole cleaning model in real cases of drilling operations and validate the model.

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LIST OF ABBREVIATIONS

μ_{app}	Apparent viscosity, cp.
μ_{eff}	Effective viscosity, cp.
CCA	Cutting concentrations in Annulus, %
CCI	Carrying capacity index.
GPM	The flow rate in gallon per mints.
HHP_b	Hydraulic horsepower of bit, hp
K	Consistency index constant, cp
n	Flow behavior index.
dP_b	The pressure drop at the drilling bit, psi.
PV	Plastic viscosity, cp.
A_a	Area of annulus, ft. Square
ROP	Rate of penetration, (ft/hr)
RPM	Revolutions per minute
FTG	Drilled Footage, ft
V_{ann}	The annular velocity, ft/mins.
V_c	The critical velocity, ft/sec.
WOB	Weight on bit, Klb
YP	Yield point, lb/100sqft

T or TRQ	Torque, (ft-Ib).
MSE	Mechanical Specific energy. (Psi)
DSE	Drilling Specific energy. (Psi)
DP	Drill-pipe outer diameter (in)
OH	Open Hole diameter (in)
TFA	Total Flow area of nozzles (in^2)
MW	Mud weight (PPG or PCF)
Fun-Vis	Funnel Viscosity (sec)
G_i, G_f	Initial Gel and Final Gel Strength
V_{cr}	The cutting rise velocity (ft/min)
V_s	The cutting slip velocity (ft/min)
D_c	The cutting diameter (in)
F_j	The Jet Impact Force (Ibs)
HSI	Hydraulic Horse Power per Square inch (Hp/in^2)
TR	Transport Ratio (%)
HCR	Hole Cleaning Ratio
TI	Transport Index.
H_{cb}	Height of Cuttings Bed (in)
H_{cri}	Height of critical region (in)
AF	Angel Factor
RF	Rheology Factor

SG	Specific gravity
D_B	Bit diameter (in)
A_B	Bit Area (in^2)
SD	Standard Deviation (statistical parameter)
LSYP	Low Share Yield point, cp
V_n	Nozzle Velocity, ft/sec
ECD	Equivalent Circulating Density, PPG
Rn	Reynold Number

LIST OF Equations

1. $\Phi 600 = (2\ \text{PV}) + \text{YP}$

2. $\Phi 300 = \text{PV} + \text{YP}$

3. $\text{K} = \frac{510\ \ \Phi 300}{510^{n}}$

4. $\text{n} = 3.32 \log \left(\frac{\Phi 600}{\Phi 300}\right)$

5. $\mu\text{app} = 0.5\ \ (\text{YP} + 2\ \ \text{PV})$

6. $\mu\text{eff} = 0.01603\ \ \rho\ (\text{PCF})\ (\text{t (Sec)} - 25)$

7. $V_{ann} = \frac{24.5GPM}{Hole\ size^{2} - OD_{pipe}{}^{2}}$

8. $V_{c} = \left(\frac{ROP}{60}\right) \frac{\frac{3.14}{4}(Hole\ size)^{2}}{144}$

9. $V_{n} = 0.32086 \frac{GPM_{mp}}{A_{t}}$

10. $V_{n} = 0.95 \left(\frac{dPb}{0.000807\text{Density ppg}}\right)^{0.5}$

11. $A_{t} = \frac{3.14}{4}\ \ n\ (number\ of\ nozzels)\ \left(\frac{(size\ of\ nozzel)}{32}\right)^{2}$

12. $dP(bit) = \text{Density ppg} \frac{GPM_{mp}{}^{2}}{120310.95^{2} A_{t}{}^{2}}$

13. $HHP = \frac{dPbGPM_{mp}}{1714}$

14. $HSI = \frac{HHP}{Hole\ size^{2}}$

$$15. TR\,\% = (1 - \frac{V_s}{V_{ft}})100$$

$$16. HCR = (\frac{Hcb}{Hcri})$$

$$17. TI = AF \;\; RF \;\; SG$$

$$18.\ RF = \frac{K \;\; TI}{3585 \;\; Aa \;\; CCI}$$

$$19. V_{cr} = \frac{60}{\left(1 - \left(\frac{OD_{pipe}}{Hole\ size}\right)^2\right) * \left(0.64 + \frac{18.16}{ROP}\right)}$$

$$20. V_{sc} = V_{ann} - V_{cr}$$

$$21. V_{sc} = \frac{24.5 \;\; GPM}{OH^2 - DP^2} - \frac{60}{\left(1 - \left(\frac{OD_{pipe}}{Hole\ size}\right)^2\right)\left(0.64 + \frac{18.16}{ROP}\right)}$$

$$22. CCA\,\% = (-0.5\left(\frac{\mathrm{Vann_{vertical}}}{V_s} - 1\right) + \left(0.25\left(\frac{\mathrm{Vann_{vertical}}}{V_s} - 1\right)^2 + \left(\frac{\mathrm{Vann_{vertical}}}{V_s}\right) V_c / \left(\frac{GPM}{7.48}\right)\right)^{0.5})100 \text{ (newtii's Method)}$$

$$23. CCA = \frac{ROP Hole\ size^2}{1471 \; GPM \; TR \; (we\ can\ replace\ it\ with\ 0.55)} \text{ (API Method)}$$

$$24. n = 3.32 \; Log\left(\frac{2PV + YP}{PV + YP}\right)$$

$$25. K = 511^{1-n}(PV - YP)$$

$$26. CCI = (\frac{Density\ (PCF)\ K\ V_{ann}}{(7.491)\ 400000}) \text{ for (Vertical wells)}$$

$$27. CCI = (\frac{K\ TI}{3585\ Aa\ RF}) \text{ for (Horizontal wells)}$$

$$28. Fj = (0.00663\ \ GPM\ \ (dPb\ MW)^{0.5}$$

$$29. MSE = (\frac{\text{Input Energy}}{Out\ ROP})$$

$$30. MSE = (\frac{480\ \ Tor\ RPM}{{D_B}^2\ ROP} + 1.273\frac{WOB}{{D_B}^2})$$

$$31. DSE = (\frac{120\Pi\ \ Tor\ RPM}{AB\ ROP} + \frac{WOB}{AB} - \frac{1980000\ \lambda\ \ HHPbit}{(AB\ \ ROP)})$$

$$32. MDSE = \frac{4WOB}{\pi {D_B}^2} + \frac{480\ RPM\ Tor}{{D_B}^2 ROP} - \frac{3{,}189{,}335\ HP_B}{{D_B}^4\ ROP}$$

$$33. ECD = MW + \left(\left(\left(\frac{0.085}{OH-DP}\right)\left(YP + \frac{PV\ Vann}{300(OH-DP)}\right)\right)7.481\right)$$

Thesis Organization

This thesis has been prepared as per the guidelines stated by the Deanship of Graduate Studies of King Fahd University of Petroleum & Minerals. It has been divided into five chapters as follows:

Chapter 1 introduces the importance of hole cleaning in well drilling.

Chapter 2 covers literature review.

Chapter 3 states the problem and research objectives.

Chapter 4 discusses the results.

Chapter 5 concludes the work with research outcomes and recommendations.

ABSTRACT

Full Name : [Mohammed Murif Al-Rubaii]

Thesis Title : [The Impact of Hole Cleaning on Rate of Penetration

Major Field : [MS Of Science of Petroleum Engineering]

Date of Degree : [Nov 2017]

Hole cleaning and drilling rate remain major challenges once it comes to plan and drill workover and development wells. Inadequate hole cleaning is responsible for a large portion of all stuck pipe problems. Approximately 33% of stuck pipe incidents are because of bad hole cleaning. The rate of penetration is strongly related to hole cleaning. If optimum hole cleaning can be achieved, that will lead to a high rate of penetration. To ensure perfect hole cleaning, it must be engineered.

There are several correlations, methods, designs, models, tools, charts, fields results, experimental studies and chemical materials to enhance the hole cleaning, but several of them are just based on theory and lack proper experimental data and not feasible in drilling operations. The knowledge of the size and density of cuttings, size of annulus, flow pattern, and down hole fluid properties cannot be determined with high accuracy using hole cleaning indicators such as Transport Ratio, Hole Cleaning Ratio or Transport Index. Cutting Concentration in Annulus (CCA) alone cannot reveal the drilling mud properties, while the application of Carrying Capacity Index (CCI) alone will not help in optimizing ROP to the desired limit.

The objective of this work is to study the impact of hole cleaning on drilling rate that will ensure optimum performance and mitigate stuck pipe problems. Knowledge from this study will help in modeling hole cleaning more accurately and therefore facilitate improving drilling rate.

The drilling parameters and mud rheological properties in certain hole sections were collected and analyzed first to determine the effect of mud properties and drilling parameters on hole cleaning and ROP performance. The data selected are from the same hole size, formation type and mud type. The relationship between mud rheological properties and CCI was then evaluated to determine how strong it is. This step helps to determine the significance of mud rheological properties on estimating CCI. CCI and CCA were then simultaneously monitored and controlled to ensure proper hole cleaning leading to optimization of the drilling operation and reduction in the drilling time. This is the first time to combine the two techniques for hole cleaning optimization.

The results of this work include guidelines for optimum recommendations for optimum drilling fluid properties and drilling parameters. The developed model has been validated using field data during drilling challenging hole sections. It has shown high drilling rate performance in the hole sections tested and helped mitigate stuck pipe incidents, improved the well drilling performance by more than 55%, mitigated stuck pipe incidents, and eliminated wiper trips, reaming trips, and pumping of sweeps as well.

The new hole cleaning model showed the importance of combining CCI and CCA to optimize the drilling operation and reduce the drilling time. The developed model can assist drilling engineers in selecting improved drilling parameters by optimizing the drilling specific energy using engineering approach (trials & errors), particles swarm optimization (PSO) method or penalty approach (PA).

ملخص الرسالة

الإسم الكامل: محمد مريف حسن الربعي

عنوان الرسالة: تأثير نظافة الحفرة على معدل الحفر

التخصص: هندسة البترول

تاريخ الدرجة العلمية: ديسمبر ٢٠١٧

نظافة الحفرة ومقدار معدل الحفر مازالا يشكلان تحديات بالغة في تخطيط وحفر الآبار التي تحتاج الى صيانة أوالآبار الجديدة التي سوف يتم حفرها في حقول النفط المكتشفة. النقص في عدم ضمان اخراج الصخور المحفورة أثنا حفر الآبار بسبب التصاق لمواصير الحفر بنسبة ٣٣ بالمئة. والخسارة الواحدة لمثل هذه الإعاقة قد تكلف على الأقل مليون دولار. إن معدل الحفر يتأثر بشكل بالغ إذا كانت الصخور المحفورة مازالت متواجدة في القسم المحفور فإذا ضمنًا أن القسم المحفور أثناء الحفر تم تنظيفه بشكل ملائم فإن ذلك سوف يقودنا إلى رفع أداء معدل الحفر.لكي نضمن نظافة تامة لابد من هندستها ضمن التخطيط مسبقا أثناء تصميم حفر آبار النفط.

هناك كثير من المطابقات والطرق والتصاميم والاودوات والرسومات والنتائج المطبقة في الحقول وتجارب دراسية ومواد كيميائية لكي تضمن نظافة الجزء المحفور من البئر و لكن كثير منها يكون نظري فقط ولا يتلائم مع عمليات الحفروينقصها أيضا البيانات التجريبية. يصعب معرفة حجم و كثافة الصخور المحفورة والفراغ البيني بين جدار الحفرة و مواصير الحفروشكل التدفق في الفراغ البيني وخصائص الطفلة المستخدمه كيمائيا في نظافة الحفرة وموازنة ضغط التكوين الصخري في أسفل الحفرة أو أثناءه و تحديدها بالدقة العالية باستخدام مؤشرات نظافة الحفرة من الصخور الناشئة أثناء الحفر مثل نسبة نقل الصخور و نسبة نظافة الحفرة أثناء الحفرو مؤشر النقل للصخور. إن معرفة مؤشر تركيز الصخور في الفراغ البيني بين جدار الحفرة ومواصير الحفر أثناء الحفر لا يكشف خواص الطفلة وأيضا تطبيق مؤشر مقدار الحمل للصخور المحفورة لا يوضح مدى تحسن معدل الحفر إلى القيمة المرغوبة.

إن الهدف من هذا العمل هو دراسة تاثير نظافة الحفرة من الصخور الناشئة أثناء الحفر على معدل الحفر وتجنب التصاق مواصير بالحفرة أثناء ذلك. إن المعرفة الناتجة عن هذه الدراسة سوف تساعد في وضع نموذج لنظافة الحفرة بدقة عالية وبناء عليه سوف يتم تحسين معدل الحفر. إن طريقة البحث إعتمدت على استخدام بيانات حقيقية مستخدمة في حفر آبار النفط في الحقول لقسم معين من الآبارودراستها وتحليلها لكي نحدد تاثير عوامل الحفر والعوامل الكيمائية لطفلة الحفر على نظافة الحفرة ومعدل الحفر. إن البيانات المستخدمة كانت من حفرة لها نفس الحجم و التكوين الصخري ونوع الطفلة.

إن العلاقــة بــين عوامــل الطفلــة ومؤشــر مقــدار الحمــل لصــخور تــم تقيمــه ومعرفــة تــاثيره علــى عوامــل الطفلة.هـذه الخطـوة تمكـن مـن معرفـة الخـواص او العوامـل التامـة المناسـبة لتكـوين الطفلة.اسـتخدام وملاحظـة موشـر مقـدار الحمـل لصـخور و موشـر تركيـز الصخورالناشـئة اثنـاء الحفـر فـي الفـراغ البينـي معـا يضـمن نضـافة عاليـه تقـود تحسـين عمليـات الحفـر وتقليـل وقـت الحفـر. دمـج هـذين الموشـرين معـا وتطبيقهمـا يكـون اول استراجية لظمان نظافة الحفرة باداء عالي جدا.

إن النتائج لهذا البحث تضم إرشادات وتوصيات لضمان تحديد عوامل حفر و طفلة عالية الأداء. لقد تم استخدام النموذج المطور (الطريقة) فعليا وتطبيقه في حقول النفط أثناء الحفر وفي طبقات الحفر المعقدة أيضا. لقد بينت النتائج أن معدل حفر أصبح أعلى بنسبة ٥٥ بالمئة زيادة على معدل الحفر الذي لم تطبق فيه الطريقة المقترحة أدى ذلك إلى تجنب التصاق مواصير الحفرو وعدم ضخ تحسينات كيميائية لنظافة الحفرة وعدم عمل عمليات تنظيف البئر الغير لازمة. إن النموذج الجديد (الطريقة) يوضح أهمية استخدام مؤشري نظافة الحفرة معا لكي يرتقي أداء عمليات الحفر ووقته. إن النموذج المطور يساعد مهندسي الحفر على اختيار العوامل المناسبة للحفر باستخدام تحسين طاقة الحفر الخاصة باستخدام طريقتي تقارب الجزيئات و التصحيح.

CHAPTER 1

1. INTRODUCTION

1.1 The Importance of Hole Cleaning.

Optimization of hole cleaning during drilling operation is very important to enhance the drilling rate, however optimum hole cleaning in drilled hole sections remains a major challenge. Hole cleaning must be engineered. The Penetration rate is highly dependent on hole cleaning. Insufficient hole cleaning can cause stuck pipe , decrement in drilling rate, significant drag and torque, Lost Circulation, wellbore instability, erratic trends in ECD, more wiper trips, back reaming, bad quality of cement jobs, bit balling and obviously increment in the cumulative cost of drilling operations and extension of the operations time.

If no attention paid to hole cleaning, such problems can finally be a root cause of losing the well. To overcome these problems, cuttings of drilling should be transferred from hole section by drilling fluid to the surface. Hole Cleaning System must fit the purpose. Hole cleaning is the key element of all design strategies. Hole cleaning is an important factor, however, the issue cannot be over emphasized in horizontal or MRC (Maximum Reservoir Contact) well in particular.

Hole cleaning is often the deciding factor between the success and failure during drilling. Historically, most stuck pipe incidents can be attributed to poor hole cleaning. It is very important to identify any wellbore stability problems that are affecting the hole cleaning before making changes to the initial planned hole cleaning strategy. Hole cleaning is more hard with oil base mud (OBM). Because of the following reasons such as: (1) the cuttings will not disband into the OBM as with water base mud (WBM) , (2) OBM is more Newtonian than WBM and (3) OBM has low thixotropic than WBM.

Cleaning of hole section is basically to increase the flow rate to have annular velocity more than slip velocity with optimizing mud rheology in order to increase the transport ratio. Theoretically, if the annular velocity is more than the slip velocity, the mud will lift the drilling cuttings and ultimately the drilling cuttings will be transported out of the wellbore. Low annular velocity can cause unwanted volume of cuttings in the annulus. Several drilling operations has proven that if the cuttings concentration or cuttings volume in annulus more than 5% can make a tight hole, a stuck pipe and loss circulation zone.

Inadequate hole cleaning can make drilling cuttings accumulate in the annulus of open hole section and the drilling rate will decrease. Drilling in complicated geological zones, such as faults, joints, fractures, layered formations, weak bedding planes, etc., normally cause instability problems of hole section. Therefore, a better understanding of the geomechanics of fracture of formation will act as an important solution to cure the problems of hole sections. The instability problems of hole section could be caused by the effect of mechanical and chemical influences or combination of them.

Mechanical effect is normally caused by the density of mud (too high or too low) and drilling mud parameters or bad practices of drilling like (penetration rate, influence of vibration, torque and drag and not performing wiper trips if hole section dictates). On the other hand, chemical effect is drilling mud type like improper drilling fluid kind or improper concentrations of inhibitors added for curing the expected formation being drilled like shaly formation.

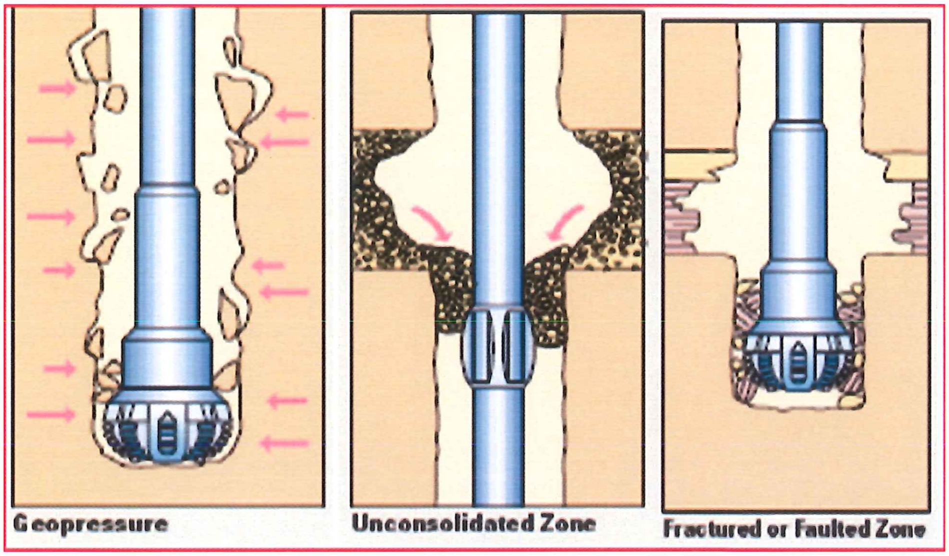

Figure 1 Tendency of Cuttings Falling VS Formation Character

If the hole starts to have sloughing or caving problems, the quantity of shale transferred to shakers will act as a normal cuttings, but large quantity could accumulate in the annulus.

The hole cleaning under the bit needs to have perfect parameters of drilling fluid to ensure efficient removal of drilling cuttings. Therefore, the plastic viscosity should be as low as possible to ensure less pressure loss across the bit and hence, jet impact force will affect more to obtain more ROP. However, the factors that are related to rate of penetration like density of drilling fluid, hydraulics of bit and drilling mud parameters should be taken in account as well.

1.2 Drilling Fluid Models.

The physical parts of any fluid flow are governed by three main ideologies, the conservation of mass, the second law of Newton and the conservation of energy. There are two types of fluids of drilling. Newtonian and non- Newtonian fluids. They mainly can describe the behavior of flow of drilling fluids.

A. **Newtonian Fluids**: viscosity of Newtonian fluids is persistent and does not change with share rate under any exposed cases of temperature and pressure such as of water, glycerin and light oil. The relationship between shear stress and share rate of Newtonian fluids is a straight line as can be shown in Figure-2.

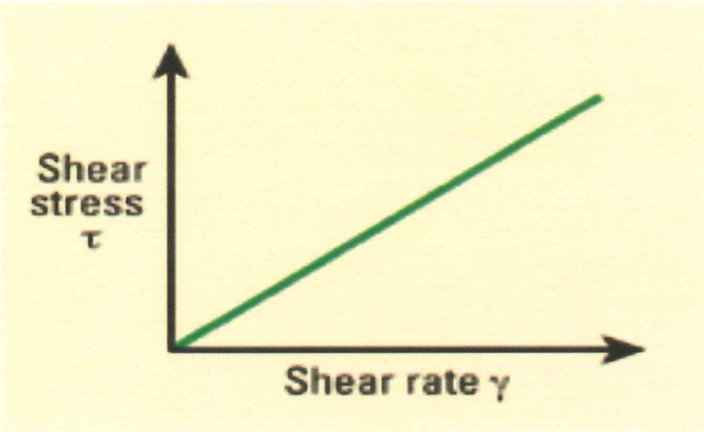

Figure 2 Flow Curve For A Newtonian Fluid (Baker Drilling Fluids Manual 2006).

B. **Non-Newtonian Fluids:** This type of fluids matches the drilling fluid in most cases does not show a straight line between shear stress and shear rate. The effective or apparent viscosity changes with shear rate. Note that viscosity changes at each shear rate, see-figure-3.

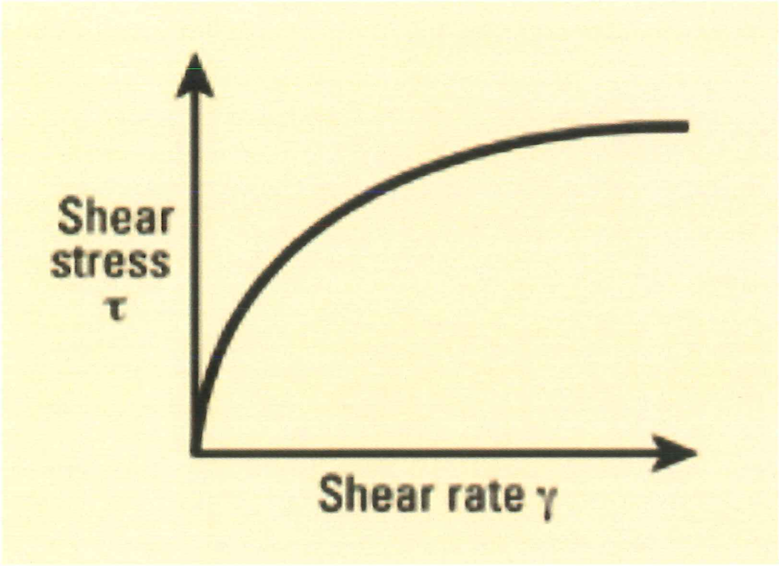

Figure 3 Flow Curve For A Non-Newtonian Fluid (Baker Drilling Fluids Manual 2006).

Non-Newtonian fluids are classified into four major categories:

- Independent of time.
- Dependent on time.

Time Independent, for instance, Bingham fluids, Power law fluids and dilatant fluids. The further group is time Dependent, Non-Newtonian Fluids such as thixotropic fluids, see figure-4 that is showing the different flow models behaviors.

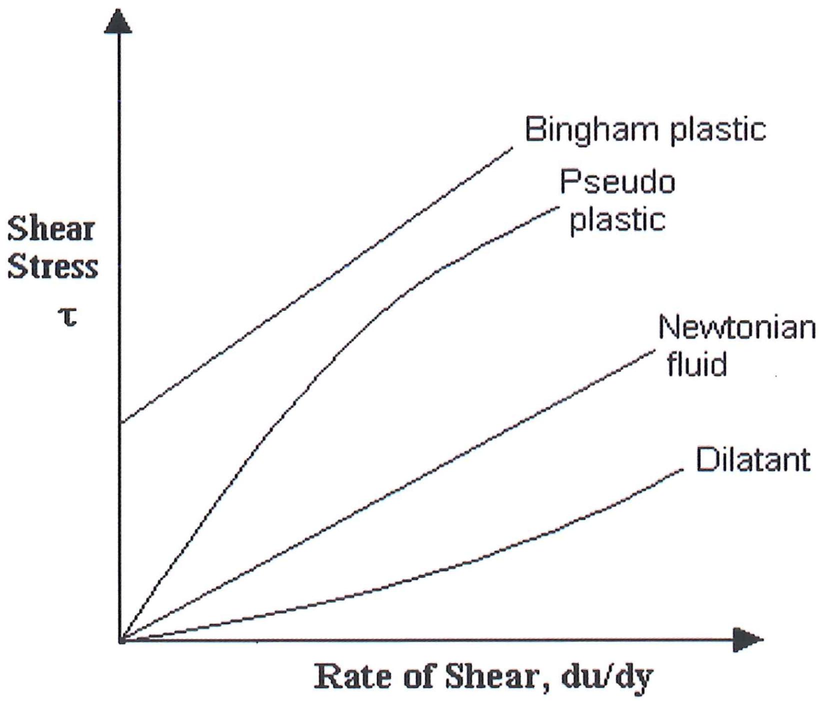

Figure 4 Flow Behaviors for Models of Fluids (Baker Drilling Fluids Manual 2006)

Bingham fluids: The relationship between shears stress and shear arte of Bingham fluids is a straight line that does not pass through the origin. To initiate the flow of this type a fixed value of shear stress must be there. This fixed value is called yield point. .

Power law fluids: The relationship between shear stress and share rate is exponential. The effective viscosity or apparent viscosity of power law fluids is decreasing with increasing shear rate. The Power Law has two parameters which they are "K" and "n". K is defined as a degree of consistency of drilling fluids at very small shear rates. The higher the value of K, the more "viscous". n can be defined as a flow behavior index and it represent the shear thinning of mud. The values of n is ranging from 0 to 1.

Dilatant Fluids: It is the fluid that has n value of power law fluids greater than 1. If the drilling fluid measurements or readings show this type of fluid, the drilling mud must be optimized. This is rarely encountered, and be happened only if the formation that is being drilled has some tart or oil that will increase the value of n to be more than 1 and that will cause high shear thinning. That might induce lost circulation problem.

Thixotropic Fluids: It is dependent on time. The gelation of drilling fluid increases with time due to the increase of yield point. The power law and Bingham fluids could be classified as thixotropic fluids if the gelation becomes present. The only way to notice the increase of gelation of drilling fluids by checking the sample or increase in pump pressure to initiate circulation, See figure – 5.

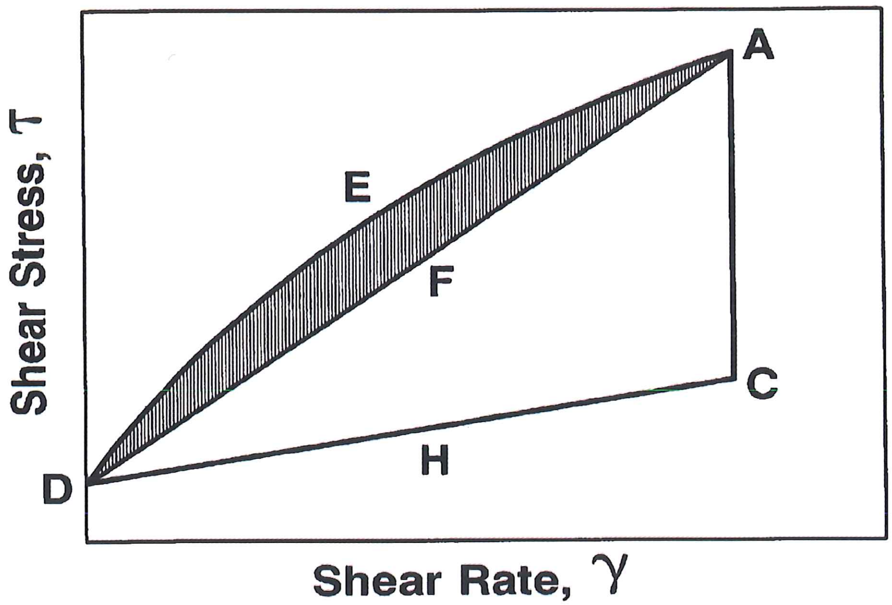

Figure 5 Thixotropic Fluid Model Behavior. (Amoco Drilling Fluid Manual).

1.3 Drilling Fluid Regimes.

While circulating the drilling fluid through circulating system, the flow of drilling mud could be laminar flow like the flow in vertical hole section or turbulent flow like the flow in deviated or horizontal hole section. Reynolds number (Rn) is an indicator that can show the type of drilling fluid flow. There are four common types of drilling fluid flow regimes such as plug, laminar, transition or unstable turbulent, and turbulent. They can be defined as follows:

- Plug Flow if the Rn is Between 100 and less than 2100.
- Laminar Flow if the Rn is less than 2100.
- Transition Flow if the Rn is greater than 2100 and less than 3200.
- Turbulent Flow where Rn is greater than 3200.

Plug Flow

Plug flow happens when the mud is thick due to the gelation at low share rate. The velocity of the mud of this flow in the center of the annulus is equal to the velocity at the wall of hole section.

Laminar Flow

The laminar flow happens when the layers of the flow overlap on each other with low mixing. Generally, it is preferred to have laminar flow in the annulus to have less pressure loss and less erosion of the wall of the hole section. In the case of laminar flow, the parameters of drilling mud should be adjusted to ensure smooth velocity profile because that will reduce the settling velocity of drilling cuttings and will ensure perfect transportation of drilling cuttings out of the hole to the surface

Transition Flow

Transition flow happens the momentum forces of the laminar flow increases due to the increase in the velocity of the mud. This is called "unstable turbulence". The Reynolds's number can indicate the transition velocity.

Turbulent Flow

The turbulent flow can be demonstrated when the drilling mud is continuously spinning and disturbed due to the high velocity of the drilling mud. The pressure loss of the circulating system increases as the turbulent flow increases because of the high velocity of flow rate of mud pump.

In this type of flow the velocity of the drilling mud at the wall of the hole section is almost zero. The velocity profile of this type of the flow is flat and basically is horizontal. The profile of flat shape can help extremely in hole cleaning efficiency and could contribute to surge the formation especially if the formation is soft or brittle which is known as washout. This may lead to reduction in cuttings removal due to more generated cuttings of washout, low quality of cementing job, zonal isolation and errors in the values of logging job. Generally, to have turbulent flow, several considerations must be taken into the account to avoid like the mentioned previous problems. The fracture limit of the formation must be provided. Normally this happened in bottom hole sections if they are vertical or deviated and horizontal. See figure-6 & 7 show the effect of velocity on pressure and types of flow regimes.

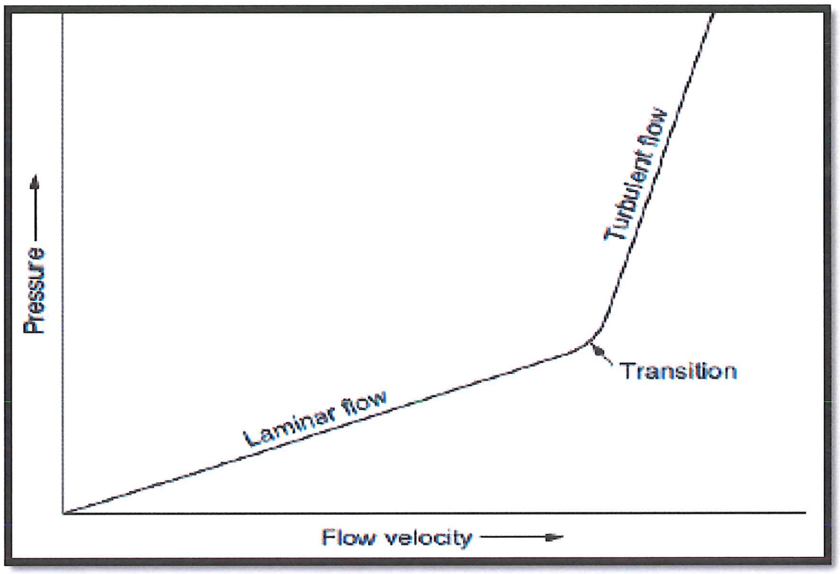

Figure 6 Schematic Diagram For Laminar, Transition And Turbulent Flow. (Composition and Properties of Drilling and Completion Fluids 2011)

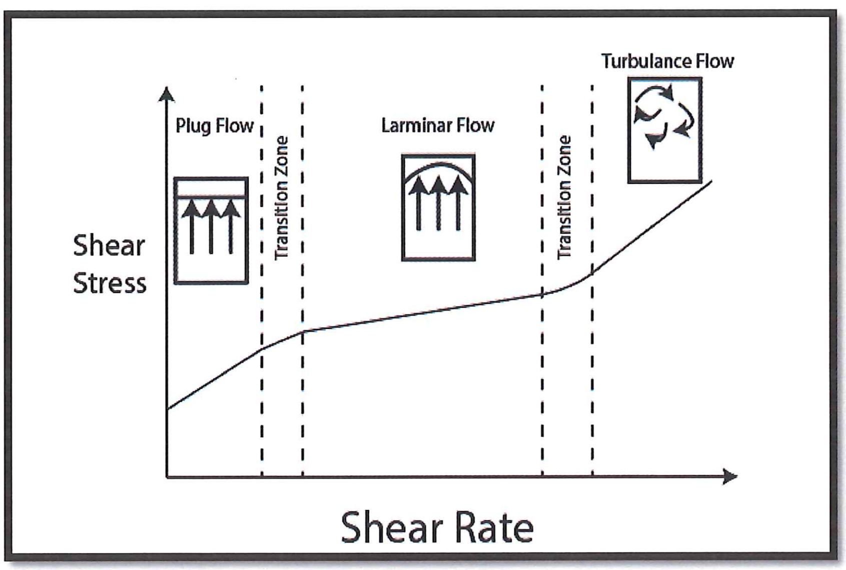

Figure 7 Flow Regime Types.

1.4 Drilling Fluid Types.

Drilling mud sorts generally are categorized by the type of base liquid used: water or oil. Water based can be fresh water, sea water or any concentration of various brine types such as sodium or potassium chloride, calcium chloride or bromide, or sodium or potassium formate. WBM, typically have bentonite, chemicals of water solubility, additives to control PH value, salts, polymers, surfactants, and deflocculants of drilling mud.

Advantages

- In offshore rigs, there is an abundance of seawater supply.
- It is economical and environmentally friendly.

Disadvantage

- Create wellbore instability (produced mainly by the hydration of clay mud having water).

Oil drilling fluids can be any hydrocarbon based fluid including diesel, mineral oil, synthetic oil, or even crude oil. Different base fluids are used to prepare drilling fluid types depending on requirements for hole stability, density, temperature of the wells as well as environmental guidelines.

Drilling fluids assortment is strong-minded by the cost effectiveness of the system to achieve the required objectives of the well or project. OBM is applied to a special type drilling liquid where oil (normally diesel oil) is the constant phase and water the discrete phase.

OBM have emulsifiers, agents of wettability, viscosifiers, agents to control filtration, and water (typically brine) to emulsify the mud formulation. These systems may also be formulated from more naturally acceptable synthetic oils and are then mentioned to as "synthetic oil-base muds" (SOBM).

Advantages

- Offers outstanding wellbore stability.
- Not as much of formation damage like WBM.

Disadvantages

- Expensive and need more watchful treatment than WBM.
- Drilling cuttings dirtied by OBM can have permanent environment influence.

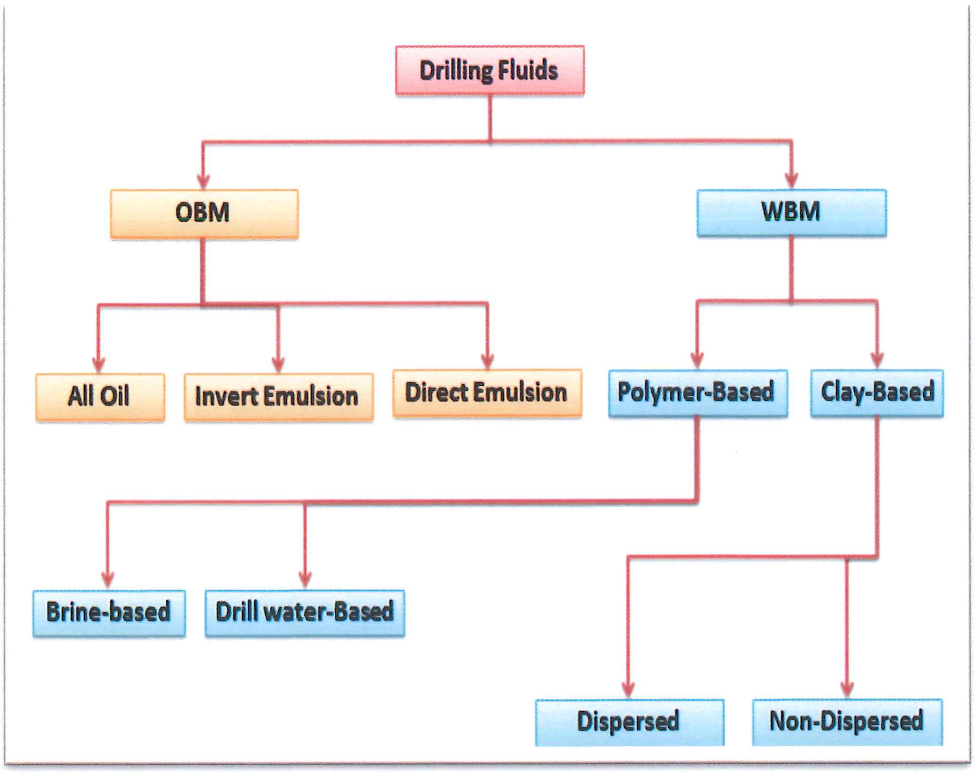

Figure 8 Flow Chart of Drilling Fluid Types

Typical drilling fluid components of water base mud and Oil Base mud

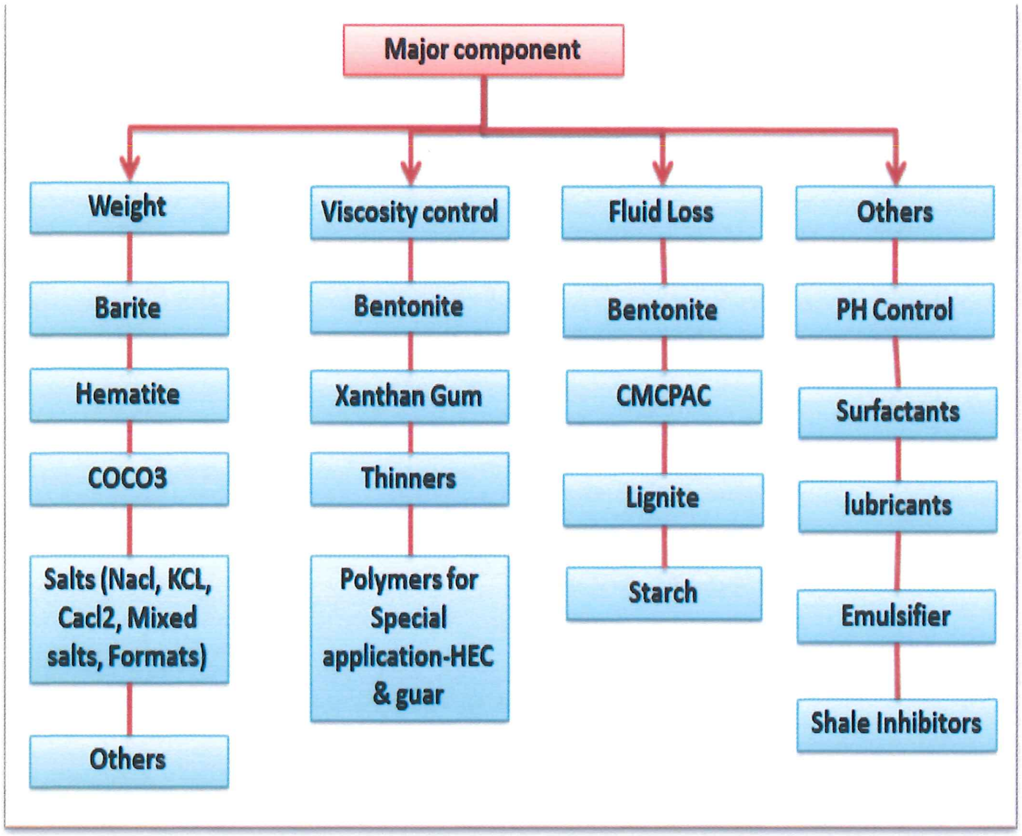

Figure 9 Drilling Fluid Components of WBM

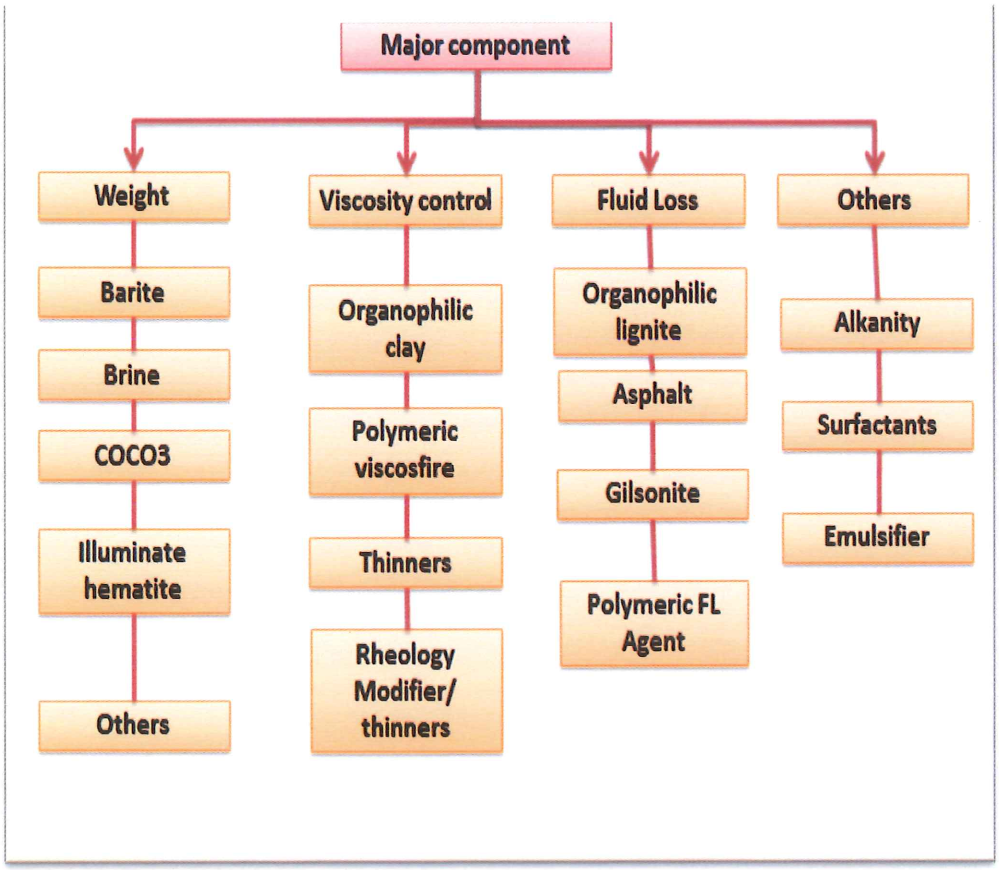

Figure 10 Flow Chart of Drilling Fluid Components of OBM

1.5 Drilling Fluid Properties.

Mud rheology properties are known to be a key variable for improving hole cleaning and enhancing drilling rate. Rheology is the science that studies matter deformation and flow. Understanding the rheology of mud is very critical, since that will contribute to know fluid flow regime, types of viscosities, capability of optimization of hole cleaning, parasitic pressures, bit pressure, and ECD (equivalent circulating density).

Mud rheological properties are the most critical factors that affect mud performance to ensure satisfactory hole cleaning and maximized rate of penetration. The Rate of penetration can be optimized effectively if the mud properties have been optimized optimally.

The focus of this work is mainly about the power low drilling fluid type. In addition, the rule of drilling fluid rheology on hole cleaning is vital. Hole cleaning is a basic function of drilling fluid to move cutting settling or cutting accumulation in the bottom side of the hole geometry especially in angle ranges from 30-60 degrees can increase the problem of the hole cleaning since the cuttings has tendency to settle fast in the low side of the deviated or horizontal hole section.

The mud properties are related to each other like shear stress, shear rate, density of mud or mud weight, funnel viscosity, plastic viscosity, apparent viscosity, effective viscosity, yield point, initial and final gel strength. They have high effect on drilling mud and subsequently, a valuable performance of drilling mud during dynamic and static conditions to enable the cuttings to be removed easily and effectively.

Shear stress is defined as the axial force divided by the surface area of a cylinder.

Shear rate is the difference in velocity between any two such cylinders, divided by the distance between them.

The density of drilling mud is defined as weight per unit volume. It is expressed as the pressure exerted by a static mud column which depends on both the density and the depth. It is designed to overcome the formation pore pressure. In addition, it has a great influence on the generated drilling cuttings to carry them to the surface especially in vertical hole section.

Viscosity it is defined as the ratio of shear stress to shear rate, and it is also the resistance to flow of the fluid. The unit of viscosity is the poise; the shear stress in dynes/cm2 divided by the shear rate in reciprocal seconds gives the viscosity in poises. Centipoise (cP), which is one hundredth of poise.

Funnel viscosity simply is a very quick test to measure the viscosity or consistency of drilling mud. So that significant changes may be noted by the mud engineer. In addition, the effective viscosity can be calculated. Pitt (2000) introduced a new formula to measure the effective viscosity by Marsh Funnel. Subsequently, the flow regime can be determined. See figure-12.

Laminar flow is preferred in vertical hole section so that laminar flow regime empower the mud to carry large amount of cuttings. The drilling string is not eccentric in the vertical hole section, hence, some of cuttings will tend to move to other side of hole. The laminar flow will support to return them to center to carry them smoothly.

$$\mu_e = \rho_M \left(t_M - 25\right)$$

Here

μ_e = the effective viscosity, cp

t_M = the Marsh Funnel (quart) time, s

ρ_M = density of mud, g/cm^3

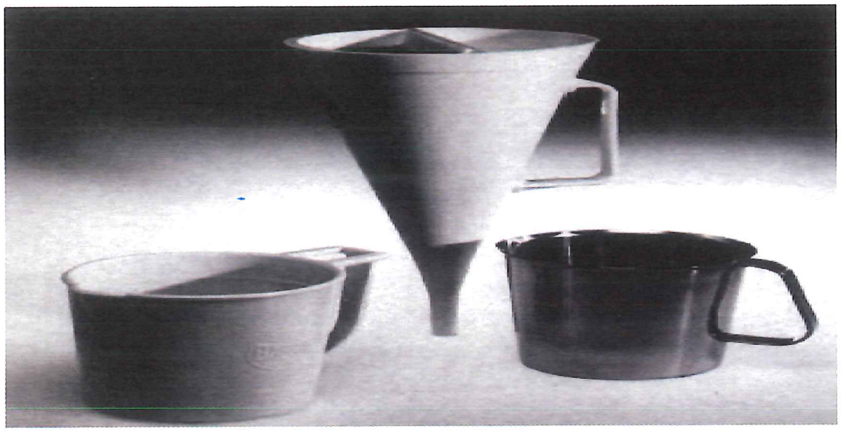

Figure 11 March Funnel and Graduated Cup

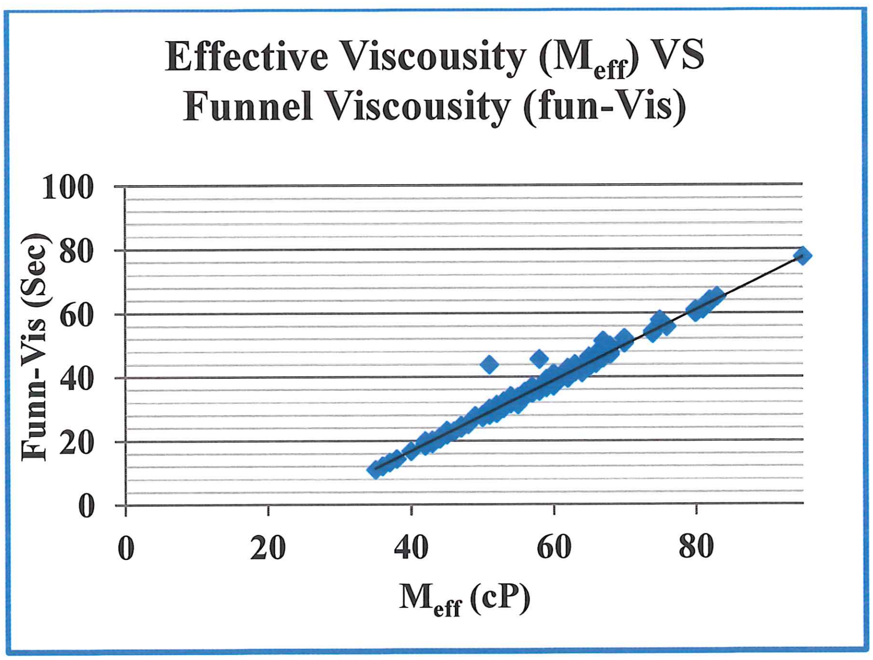

Figure 12 Effective Viscosity VS Funnel Viscosity

Effective Viscosity or Apparent Viscosity is defined as the shear stress divided by the shear rate (at any given rate of shear) is known as the effective or apparent viscosity. Apparent viscosity decreases as the shear rate increases. They also can be calculated from the reading R-600 of G-viscometer divided by 2. They have strong relation with plastic viscosity as shown in figure-13.

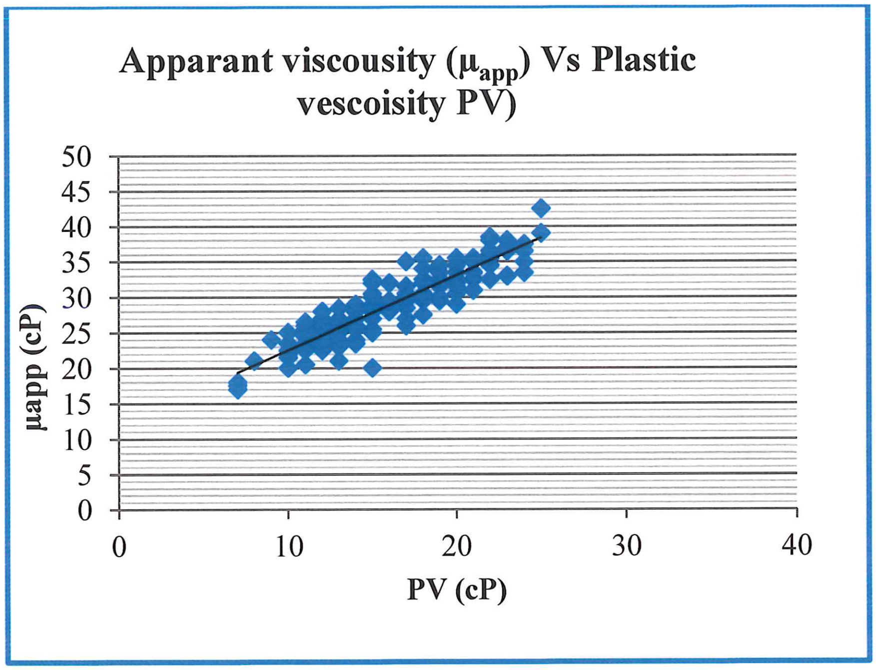

Figure 13 Apparant Viscosity (µapp) VS Plastic Viscosity (PV)

Plastic viscosity represents the ratio of incremental changes in shear stress to shear rate. It is the result of mechanical interference between the solid particles and the fluid. It is mostly a function of total surface area of the solids. Additionally, Plastic viscosity is a mechanical resistance to flow. It tells us something about the expected behavior of the mud at the bit. One of our design criteria was to minimize the high shear rate viscosity.

A decrease in plastic viscosity should be a signal corresponding decrease in the viscosity at the bit, less flow behavior index and less Reynolds number. Consequently, a higher penetration rate could be obtained see figure -14, 15, 16 & 17.

The increase in pressure drop of the drill string on the bottom, caused by an increase in PV, would lessen the offered flow rate and have a habit of decrease in lifting ability. High plastic viscosity is never wanted and should be kept low. Minimum plastic viscosity can be reached if the mud is kept reduced of drilled solids or by dilution.

Figure-18 shows rules for plastic viscosity of WBM at various mud weights. Lower curve represents muds that contain only barite and sufficient bentonite to suspend the barite. This curve should denote minimum plastic viscosities for good mud performance. The temperature has an effect on plastic viscosity, but that will be serious in HPHT (High Pressure & High Temperature) wells with water based mud see figure -19. The unit of measurement is centipois. It can be calculated from the reading R-600 and R-300 of viscometer. PV = R-600 – R-300.

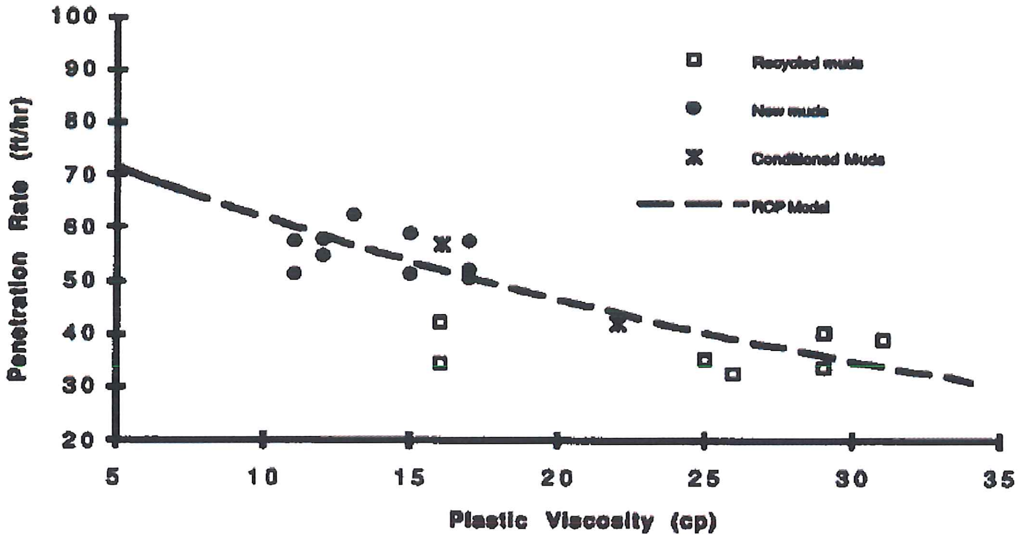

Figure 14 Relationship Between Plastic Viscosity And Penetration Rate. (Beck 1995).

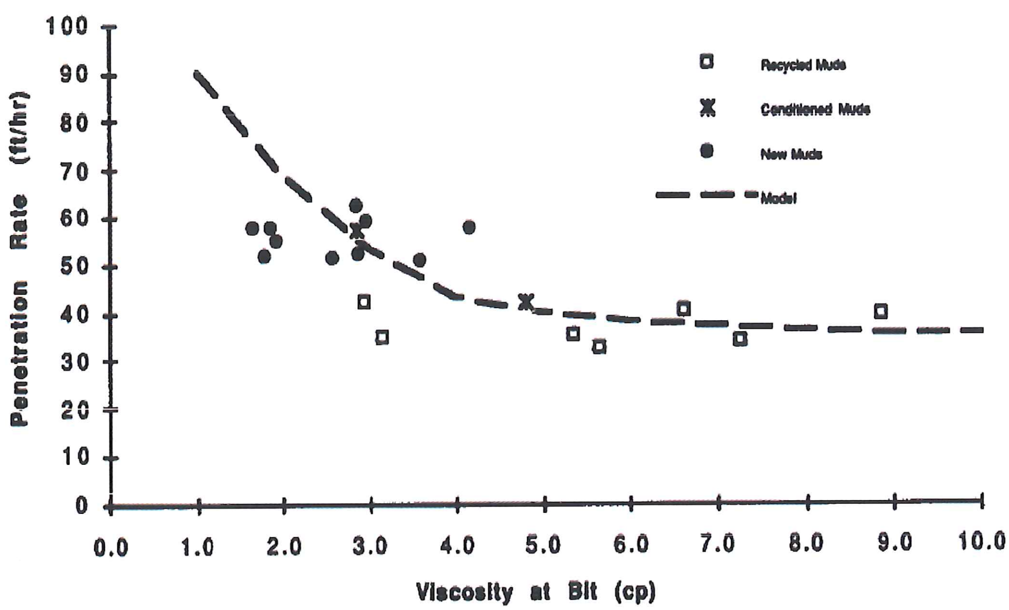

Figure 15 Relationship Between Viscosity At Bit And Penetration Rate. (Beck 1995).

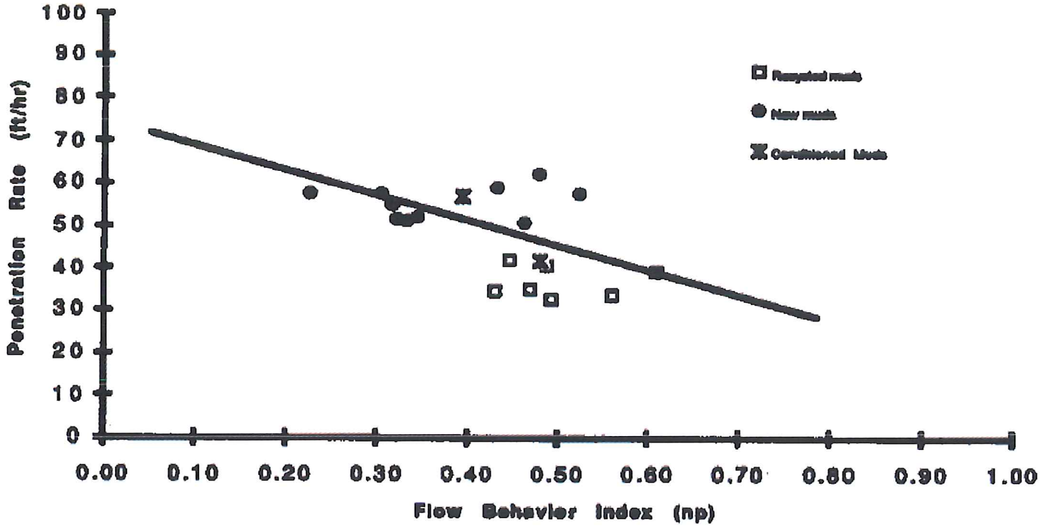

Figure 16 Relationship Between Flow Behavior Index And Penetration Rate. (Beck 1995).

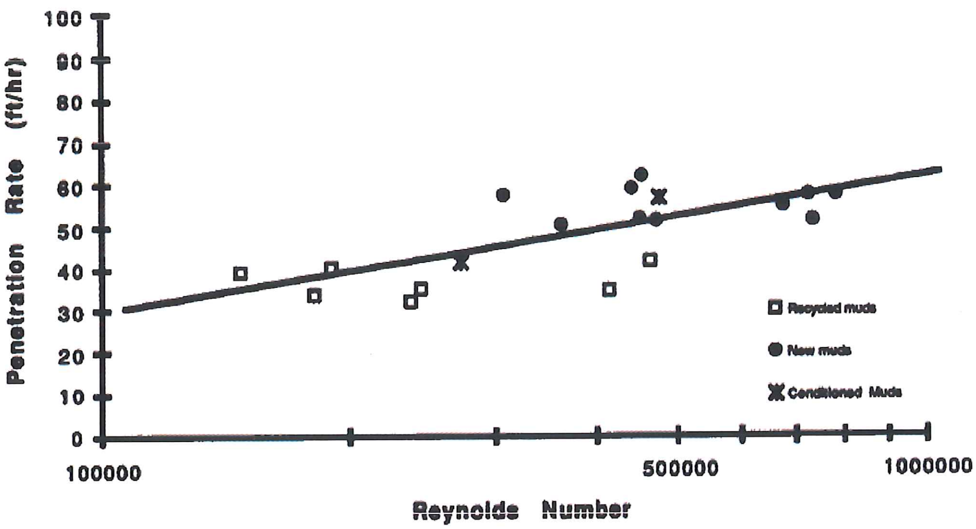

Figure 17 Relationship Between Reynolds Number And Penetration Rate. (Beck 1995).

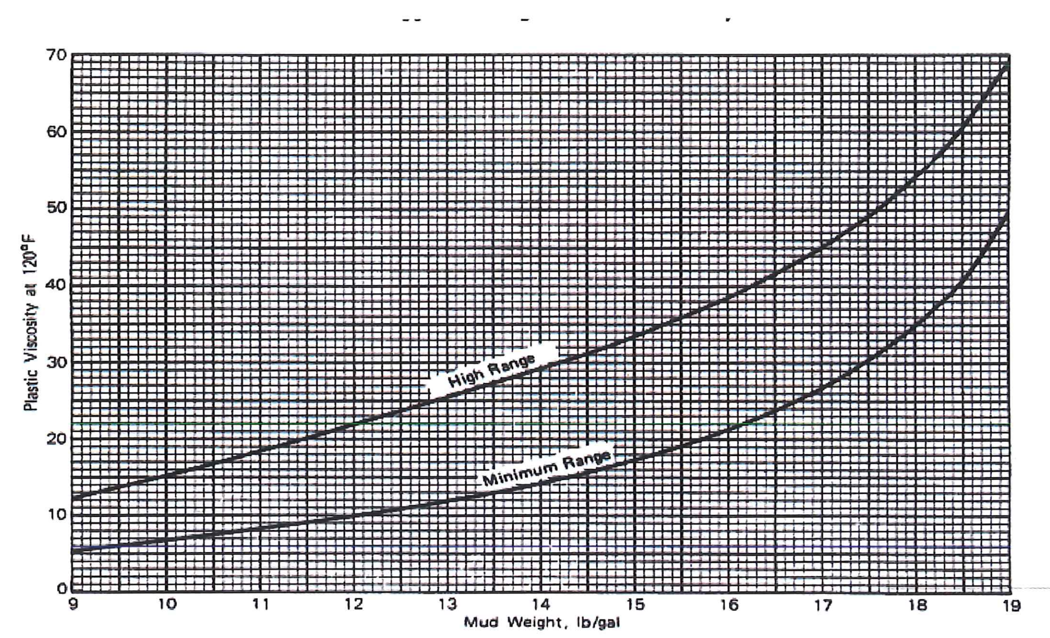

Figure 18 Plastic Viscosity Vs Mud Weight. (Max & Martin 1974)

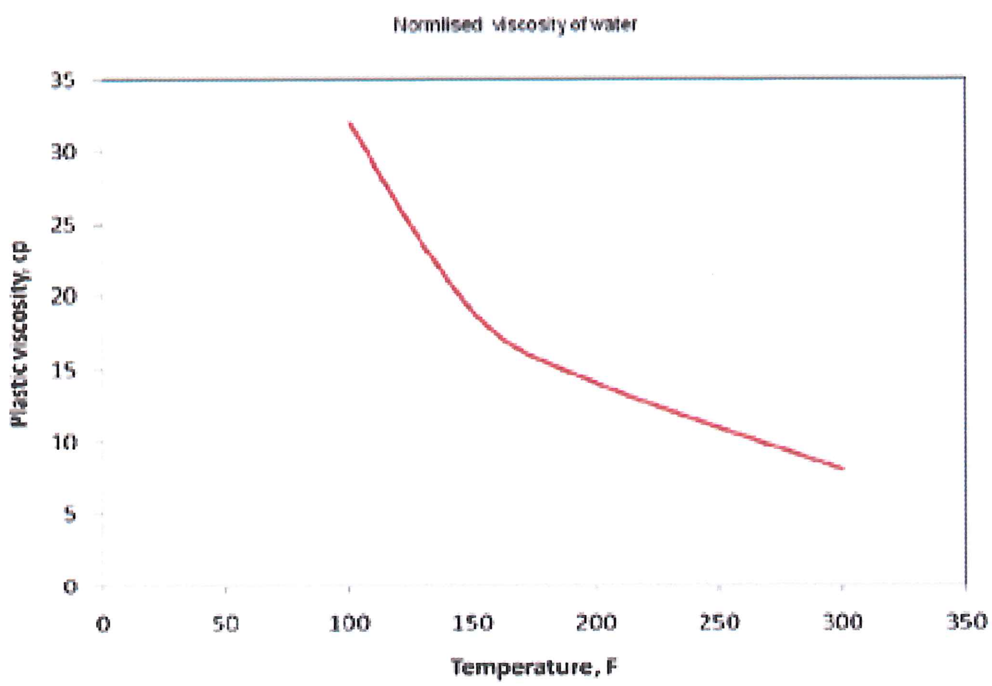

Figure 19 The Effect Of Temperature On Plastic Viscosity With WBM. (Qahtani 2010)

Yield point represents the force required to initiate the flow, or causes the molecules to shear past each other. It is also, a measure of the ability of the solid particles in fluid to build a structure that resists deformation. YP represents an electrochemical resistance to flow. In fact, it is normally close to the value of the shear stress at annular shear rates. **On other words, it is the ability of mud to carry cuttings in dynamic conditions (mud pump is on).**

Whatever that causes variations in the low shear rate viscosities will be reflected in the yield point. It is a good pointer of flow behavior in the annulus and compositional variations that disturb the flow behavior in the annulus.

A greater yield point raises the transport capacity of the mud and builds up the circulating pressure drop in the annulus. The larger particle size in annulus, the higher yield point is required to carry as shown in figure-20, Bentonite has a major impact on yield point, can be added to the additives of drilling fluids to increase it, see figure-21. A yield point range for various weight muds is shown in Figure-22. YP also has some relationship with critical or minimum flow rate required to move cuttings see- figure -23. It can be calculated from the reading R-300 of viscometer and PV. YP = R-300 – PV. The unit of YP is $lb/100^2$.

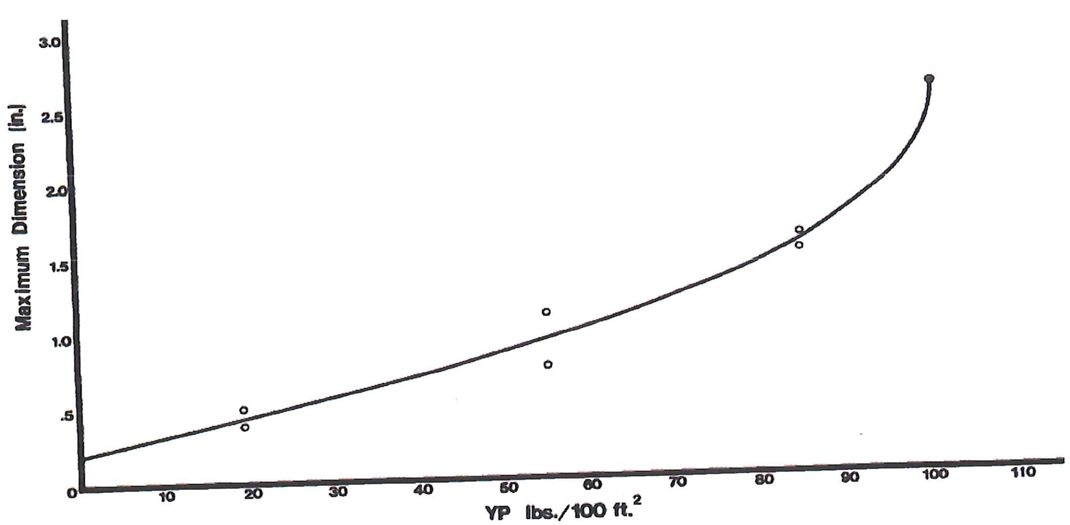

Figure 20 Required Yield Point to Remove Varying Particle Size (Brien 1985)

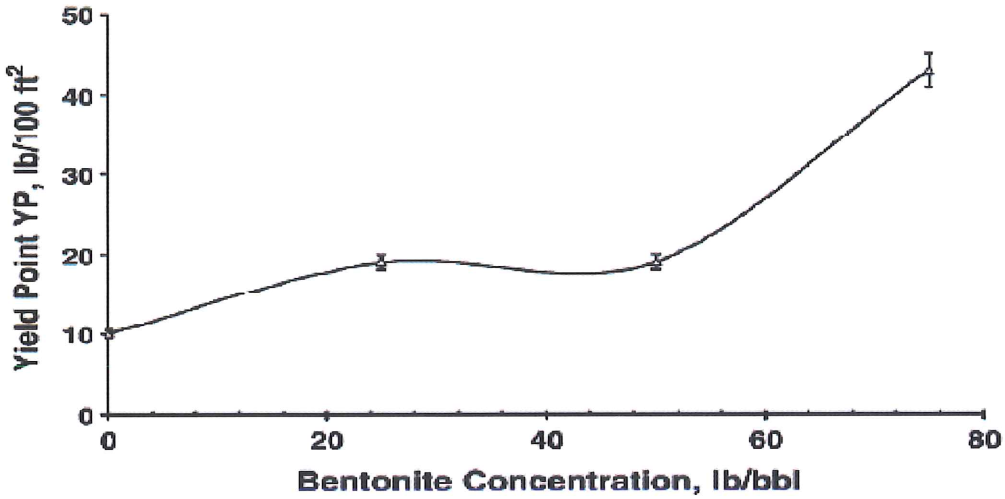

Figure 21 Effect Of Bentonite Concentration On Yield Point (Derrick 2006).

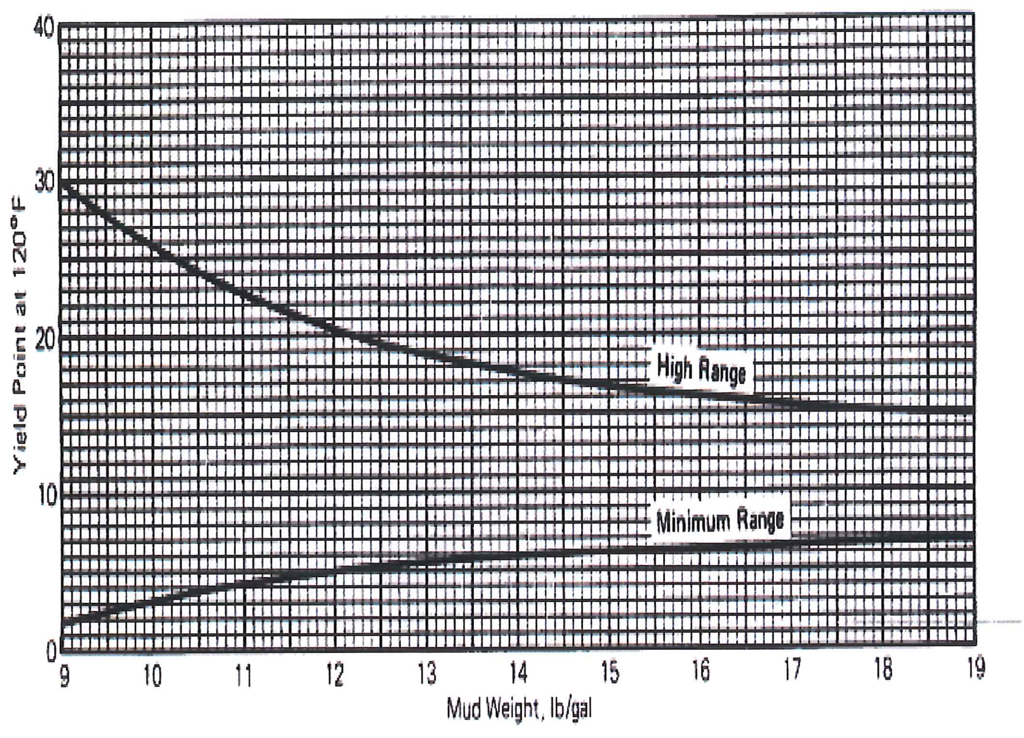

Figure 22 Yield Point VS Mud Weight. (Max & Martin 1974)

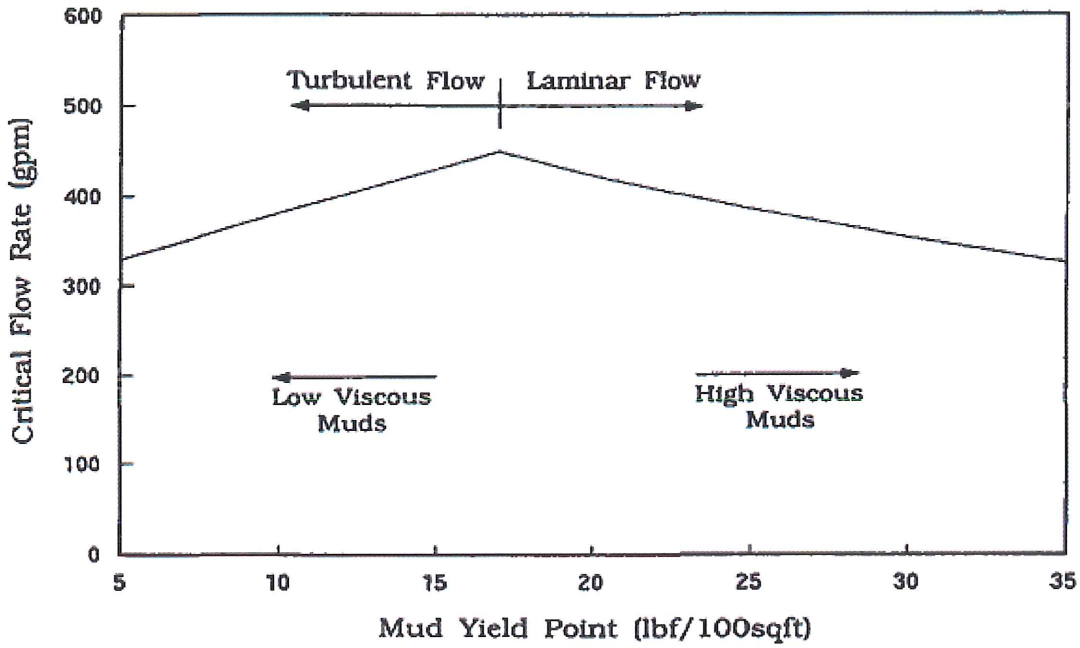

Figure 23 Effect of Yield Point on Critical Flow Rate (Luo 1992)

Initial and final gel strength is the forces between the internal particles. Gel strength is the ability of the dispersion of colloidal solids to form a gelation of drilling fluid to resist the shear. **Simply it is the ability of mud to carry cuttings in static conditions (mud pump is off)**.

Essentially, the true yield point and gel strength of Bingham fluid is the same. To measure the gelation of drilling mud, the viscometer is set on 3 RPM for 10 sec. to read the value of 10 sec initial gel strength. After 10 min the drilling mud is read to record the value of 10 min gel strength.

The unit of gel strength is the same as the yield point ($lb/100^2$). This measure can demonstrate that is the mud pump got shutdown and the drilling mud is static the gelation increase and that means more pressure you need to initiate the circulation and this may cause loss of circulation after operating the mud pump. It is desirable to be as low-flat with time as shown in figure-24.

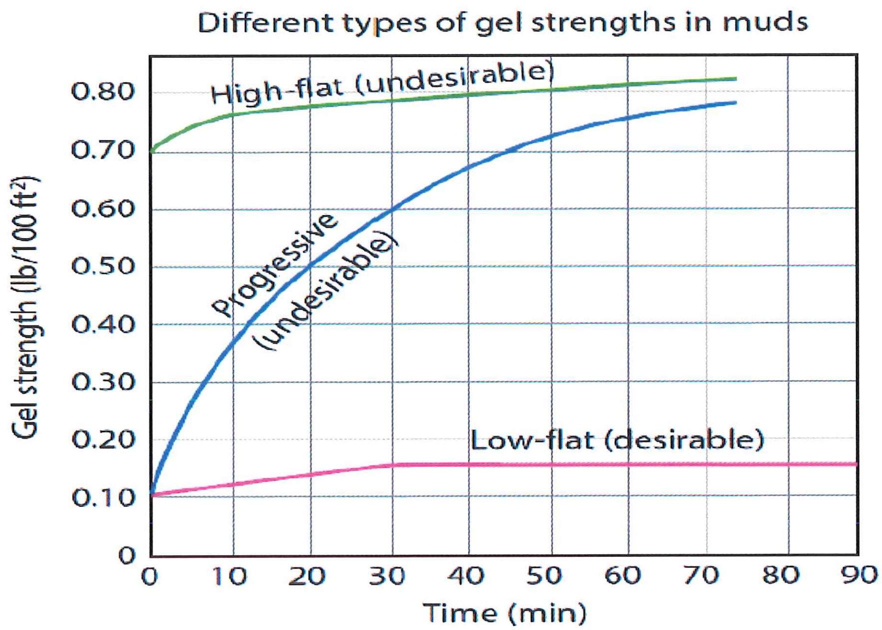

Figure 24 Gel Strength VS Time (Fundamental Sustainable Drilling Engineering Book 2015).

Electrical stability (ES) is a rheological property of the oil base mud systems which it measures the strength of the oil water phase, and is measured in volts. The lower the oil/water ratio the lower the emulsion strength. Simply, ES measures how emulsion of OBM and the continuous oil phase are strong.

If the mud is new, then it will require two or three circulations through the bit to build its strength. Typically, OBM requies more modified bentonite (organopholic caly) and emlulsifier that will lower the ES of drilling mud once it will be compared with diesel base mud formulation. So, ES contributes to control the emulsion of OBM which that indicates the wettability and emulsion of quality of the sample.

The understanding of ES readings is not fully compherhended, however, there were several studies were introduced to releate between the wettablilty of oil drop lets and solids that were added to the OBM system or desel base mud system and how the emulsion of the OBM is stable.

To measure the ES, mud sample is collected in a cup and insert the brope of the device that measure the ES inside the mud sample at 120°F (48.8°C) pushing button of device to read the value (derrick 2006). Maximum voltage that the mud will withstand across the gap before showing current is showed as the ES voltage.

It is also affected by the addition of bentonite to the mud. ES decreses as the concentration of modified bentonite (organopholic caly) increases. The organopholic clay is reactive that will reduce the surfacatant and emulsiferes in the OBM system. Therefore, the stability of the continuous oil phase will be disturbed. The addition of modified benonite will decrease the emulsion of the drilling mud, that will affect the ES as shown in figure-25.

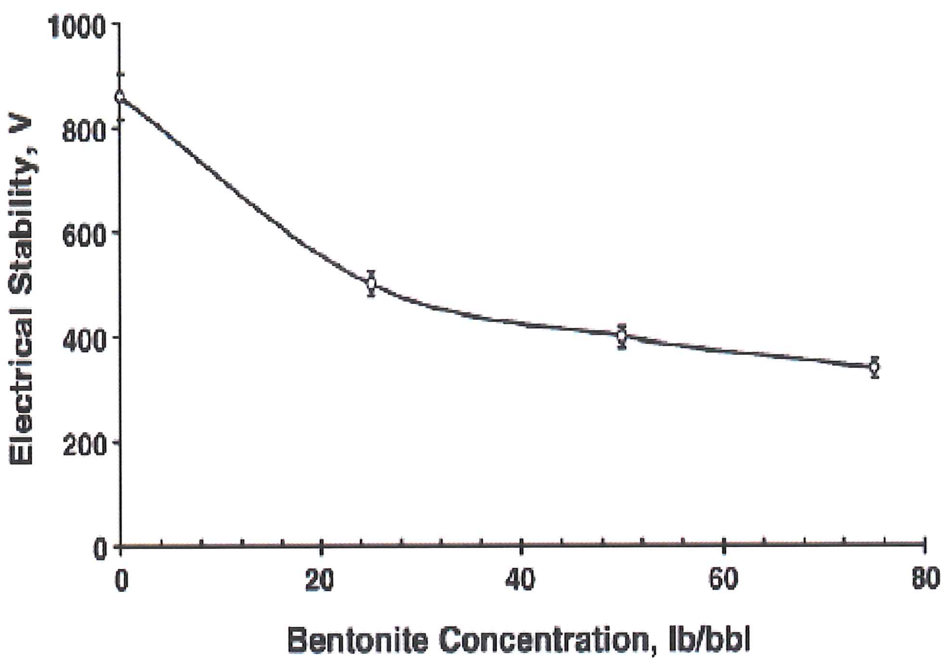

Figure 25 Effect Of Bentonite Concentration On Electrical Stability (Derrick 2006).

6-RPM and 3-RPM readings of Viscometer are improtant readings that indicate how effective is the low shear yield point (LSYP) of drilling fluid. It has a major impact on hole cleaning in devaited and horizontal sections. The 6 RPM FANN reading should be maintained at least at 1.2 – 1.5 times the hole diameter for inclination > 35 deg as arule of thumb that is applied by some oil operators.

Filter cake or Filtration occurs when the mud pressure is higher than the pore pressure and mud penetrates the pores of the formation. This infiltration should be controlled to avoid formation damage. Filter cake must be optimized to be thin, impearmable and tough, but not too much tough since this will cause cleaning problems.

Drilling rate was qualitatively related to the difference between the measured rates of filteration (filter cake) while drilling and circulating. The filter cake pressure drop has an effect on the drilling rate as shown in figure- 26. That means should be impearmable and tough sufficiently to reduce from the pressre drop across it by reducing the volume of filteration to reduce of building of filter cake. Drilling mud can cause damage to formation by mud solid invasion and mud filtrate invasion.

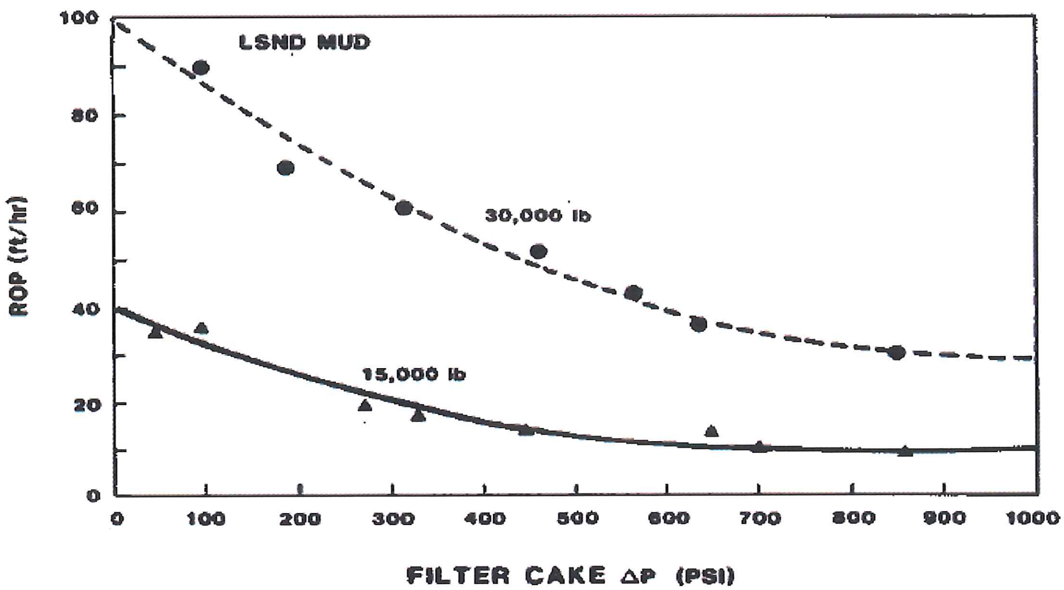

Figure 26 Penetration Rate Vs Filter Cake Pressure Drop (Black 1983).

Mud sloid invasion, mud solids impair productivity by two primary ways: plugging of pore throats & increase in capillary pressure. It can be controlled by selecting optimum size of weighting solids material like KCl (potassium formate or potassium cloride), (Manganes tetraoxide) Mn_3O_4 & Calcium Carbonate and barite ($Caco_3$/ barite). The below table-1 give a rough idea of the required maximum bridging particle size (Glenn & Slusser 1957)

Permeability, mD	Maximum Particle Size, µm
100	2
100–1,000	10
1,000–10,000	74 (200 mesh)

Table 1 The Required Maximum Bridging Particle Size (Glenn & Slusser 1957).

Mud Filtrate Invasion , all muds are formulated to form a layer (mud cake) at the walls of the wellbore. Two types of mud filtrate invasion such as dynamic filtration which occurs above the bit while the mud is circulating. The rate of fluid loss during this stage is normally higher than that during tripping. The other type is a static filtration, this occurs during tripping or periods of non-circulation.

The are four major filter cake parameters (Economides 1993) .

- The dynamic fluid loss coefficient for the filter cake. Fluid loss coefficient can be determined from the laboratory ($\frac{in^3}{in^2.hr^{\frac{1}{2}}}$).
- The exposure time (hr)
- Constant accounting for the mechanical stability of the filter cake called (b). Reported values of b from lab $2\ x\ 10^{-8}\ to\ 5\ x\ 10^{-7}.(\frac{Cm^3}{Cm^2})$.
- The shear rate at the wall, (Sec^{-1})

The most important parametre of filter cake is the dynamic fluid loss cofficient of filter cake. The optimization of this parameter will make the filter tough by forming stong clustring structure of filter cake. This optimization has a major impact of reduction of the invasion lenghth of drilling mud inside formation. It can reduces skin factor as well. Once the mud cake reaches the correct thickness wich is perrfed to be 1/32 to 2/32 inches, invasion slows down and stops. The filter cake building properties of mud can be measured by means of a filter press device. In Figure-27 we can see how mud cake is invading to the formation.

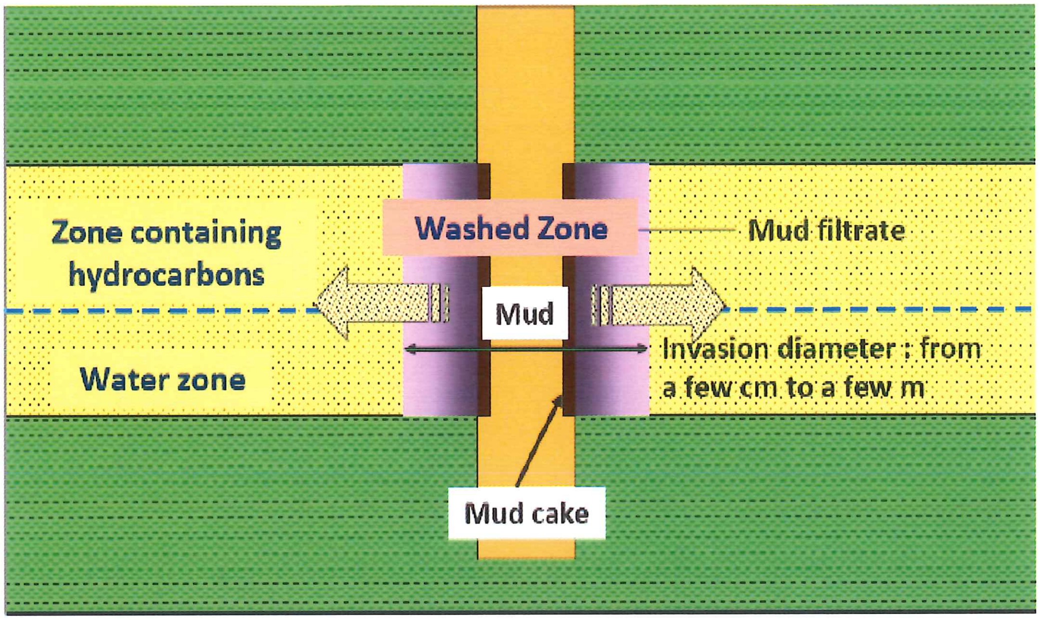

Figure 27 Mud Filtrate. (Ferreira 2012)

Sand Content is a simple test to see the percent by volume of sand in a drilling fluid, for example, What is the percent of solids will not pass through a 200 meshscreen. Simply, it is the proportion of sand in the mud. It is not preffered to be high to avoid mud pump liner damage (washout), increase (equivelnt circulating density) ECD and change mud density while drilling.

Low Gravitety Solid (LGS) normally it is assumed to have density of 2.6 g/cm^3. Drilled solid and solids that are added to the drilling mud of additives are considered as LGS. LGS can increase the mud wight and that could lead to loss of circulation since the mud weight has effectively increase more than the equivelent mud weight of drilled formation due to entered soilds. Certain equiment should be added to mud system equipment which is the centerfuige device. Fine solid is supposed to be removed from the mud. Rebonson (2004) found relation between the mud weight and LGS. Mud weight increases as LGS increases, hence the plastic viscosity increases as well, see-figure-28.

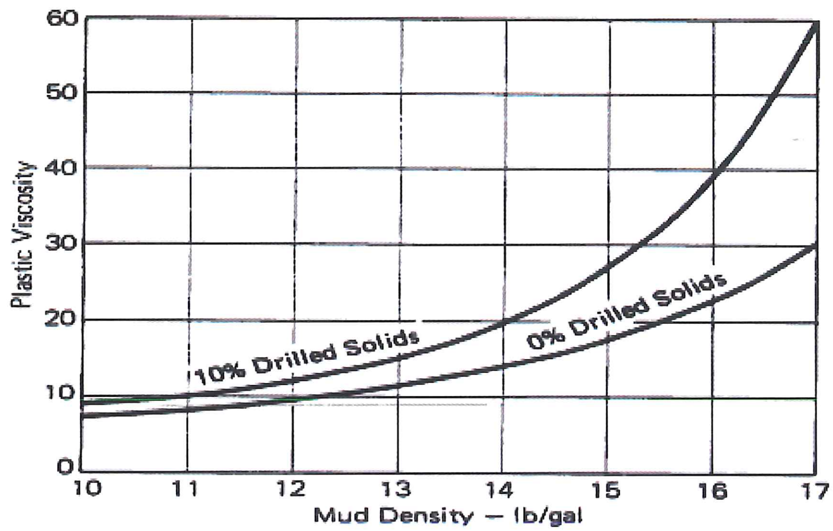

Figure 28 Plastic Viscosity Vs Mud Weight With Effect Of Drilled Solids. (Max & Martin 1974)

PH is a measure of the acidity or alkalinity of the mixing water. At room temperature the ion product constant of water Kw, has a value of $1\ x\ 10^{-14}$ mol/l. For pure water [H+] = [OH-] = $1\ x\ 10^{-7}$and pH = 7. The product of [H+] and [OH-] must remain constant. It is the logarithm of the reciprocal of the H concentrationin grams moles per liter, which can be mathematically expressed as: $PH = -\log(H^{+})$.

Methyl Blue Test (MBT) is also called the Cation Exchange Capacity (CEC). This measures the concentration, in lb/bbl, of clays in the mud. For a mud to be manageable this should not be allowed to go above 30 ppb. It has a notable influence on rate of penetration see figure-29.

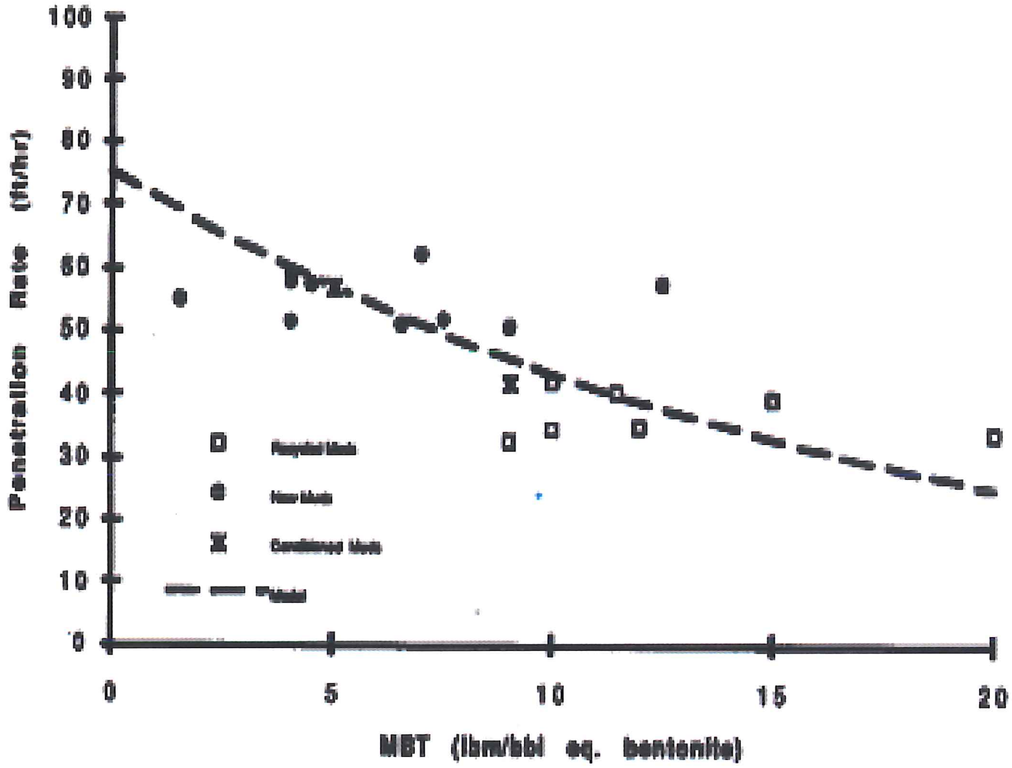

Figure 29 Relationship Between MBT and Penetration Rate (Beck 1995).

Chlorides and Hardness these are both chemical titration tests to establish the concentration of Cl^{-} and hardness ions (Mg^{2+} and Ca^{2+}) in the mud, measured in mgl. These tests are performed on the filtrate from the fluid loss test.

Thixotropic property the gelstrength of some muds, notably fresh water clay muds, increases with time after agitation has ceased , aphenomenon that is known as thixotropy.

Shear thinning Property is defined as the increase in share rate that will reduce the effective viscosity. The ratio of the plastic viscosity to the yield point (PV/YP) which shows the measure of shear thinning. The higher the ratio the greater the shear thinning. Table-2 demonstarte the fuction and idea of drilling fluid parameters.

Function	Physical/Chemical property
Transport cuttings from wellbore	YP, apparent viscosity, velocity, gel strength
Prevent formation fluid flowing into the wellbore	Density
Maintain wellbore stability	Density, reactive with clay
Cool and lubricate the bit	Density, velocity
Transmit hydraulic horsepower to bit	Velocity, density and viscosity

Table 2 Function and Physical Properties Of Drilling Fluid (Heriot Watt University, 2012)

1.6 Factors Affecting Hole Cleaning in Vertical, Deviated and Horizontal sections.

Hole cleaning in vertical hole sections concentrates on flow rate and mud rheology. The objective is to deliver a flat flow profile. In a deviated and horizontal hole sections, hole cleaning concentrates on flow rate, pipe rotation, and mud rheology.

The same factors which affect hole cleaning in a vertical hole section also affect hole cleaning in a deviated and horizontal hole sections. The single major effect on hole cleaning in deviated and horizontal sections is the angle of inclination. The inclination will form cuttings bed and increase the settling tendency of drilling cuttings. Cuttings beds will increase the volumetric drilling cuttings concentration in annulus (Mitchel 2001).

Examples of hole cleaning approaches such as 1-drilling fluid properties (Rheology, inhibition, colloidal solids), 2- Bit & Bottom Hole Assembly (BHA) Designs (Allowable RPM and reciprocation , bypass area and ROP),3- hydraulics (Available GPM, pressure limits, ECDs, BHA requirements & limits, shaker loading limits) and 4- Rig Systems (Limitations for top drive (RPM VS Torque), solids control, pumps, electrical power.

1.6.1 Factors Affecting Hole Cleaning in Vertical Hole Sections:

There are several factors that can have deep impact on hole cleaning in vertical hole which include the following:

- Pipe Rotation (RPM)
- Rate of penetration (ROP).
- Flow rate/annular velocity.
- Drilling-fluid density.
- Drilling-fluid rheology.
- Cutting size, shape and density.

Rishi (2000) ranked these factors of hole cleaning during drilling.

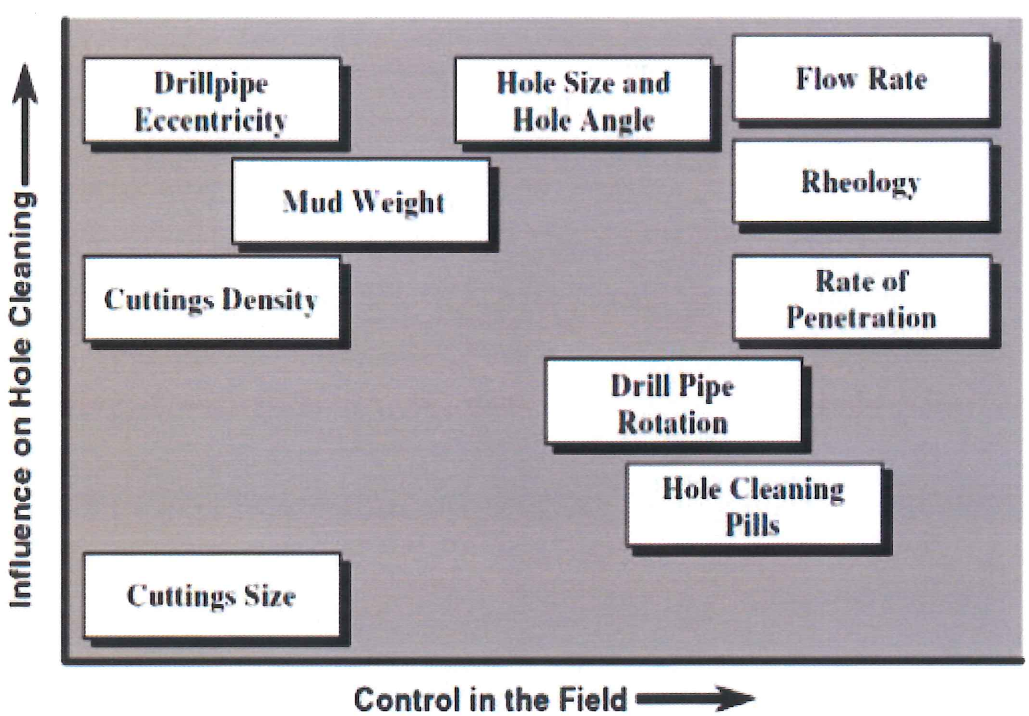

Figure 30 Key Variables Controlling Cuttings Transport-[Rishi 2000]

In addition, some field studies have shown the effect of pipe rotation to agitate the cuttings and help flow rate to move cuttings faster .If drilling mud has optimum mud rheology like plastic viscosity (PV), point of yield (Yp), initial and final strength of gelation (GI & GF), which will contribute to enhance hole cleaning significantly. To effectively remove drill cuttings during drilling, a number of factors must be put in place to achieve optimal bottom hole cleaning.

- **Drill Pipe Rotation**

Drill Pipe Rotation is important to change flow regime from laminar to turbulence. In vertical hole section the drill string is not eccentric in the wellbore. That will lead drilling cuttings to migrate to the other side of the wall of wellbore. Laminar flow has maximum velocity in the center. It is recommended to rotate the drilling string to move drilling cuttings to center to enable the flow rate to lift them easily.

Also, Williams and Bruce (1951) studies that pipe rotation initiates the unstable turbulent flow regime which will take them to center, hence the annular velocity will lift them to surface. The unstable turbulent flow regime can cause increment in shear stress on the drilling cutting surface. Shear stress will support to move drilling cutting, see figure -31& 32. Tobenna (2010) mentioned that the impact of drill pipe rotation on hole cleaning is relatively small in vertical well but more significant in inclined wells.

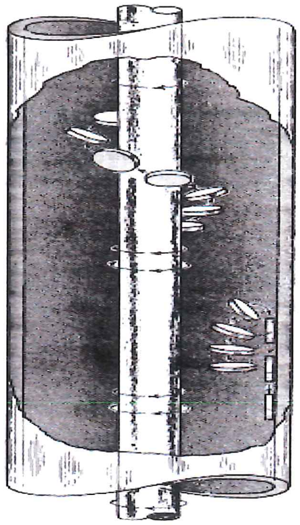

Figure 31 Pipe Rotation Effect On Drilling Cuttings In Vertical Hole. (Williams 1951)

Figure 32 Rpm Helps Fluid Flow in the Narrow Side of an Eccentric Annulus (Tobenna 2010)

- **Rate of penetration**

Drilling rate has a major impact on cuttings transport and hole cleaning. As the drilling rate increases, the drilling cuttings volume load in the annulus also increases as shown in figure-33. For efficient transport of cuttings and hole cleaning ROP should be controlled. Fast drilling, generates more drilling cuttings which may lead to drilling cuttings accumulation in the annulus and shale shakers especially when drilling across sticky and clay lithology of formation.

There is always room or opportunity to optimize ROP if optimum flow rate and pipe rotation can be achieved. If mud pump and top drive system of rig are limited to obtain an adequate flow rate and enough RPM, the drilling rate must be controlled.

A reduction in ROP may have an influential impact on drilling costs, however, the benefit of avoiding other drilling problems, such as mechanical pipe sticking or excessive torque and drag, can compensate for the loss in ROP. Drilling rate can be controlled by minimizing cuttings concentration in annulus and critical velocity, see figure-34.

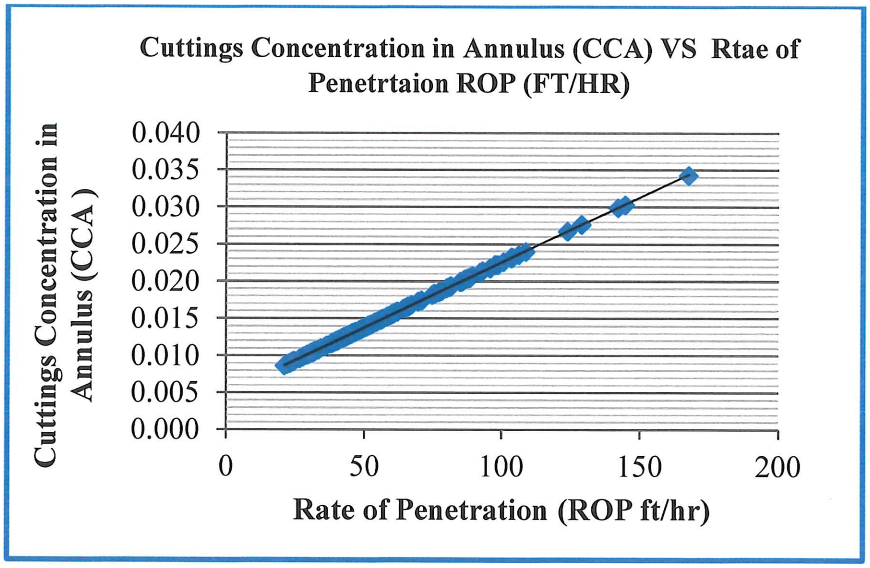

Figure 33 Relationship Between Cuttings Volume In Annulus And Drilling Rate.

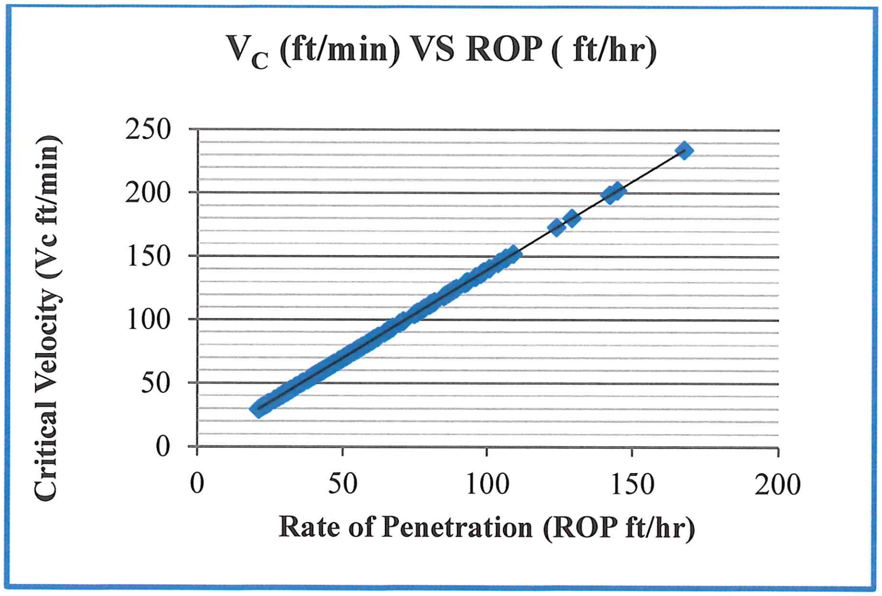

Figure 34 Relationship Between Critical Velocity And Drilling Rate.

- **Flow rate**

Flow rate is an influential factor that affects hole cleaning efficiency in a vertical hole section. Flow rate helps the lifting force through momentum transfer and friction because the mud strikes and slips past the drilling cuttings. The momentum transfer increase with flow rate in laminar flow. the flow rate and flow regime are affected by hole sizes. In surfaces hole sections or large hole sections the flow regime is laminar. The contribution of flow rate depends on mud weight, if the mud weight is low and drilling parameters is not optimized, there would be low contribution to hole cleaning from flow rate.

- **Mud weight**

Mud weight influences hole cleaning in three manners, provides buoyancy effect to help lift the cuttings, affects the momentum of the fluid and affects the friction the fluid that can impact drilling cuttings once they pass through it. Mud weight can effect on the slip velocity of cuttings and then optimize the transport ratio. Nothing contributes to slip velocity reduction and hole cleaning in vertical hole section more than mud weight. Increasing the mud weight across narrow window (small margin between pore pressure and fracture pressure) or expected lost circulation zone will not be acceptable, so, mud rheology must be optimized.

- **Mud rheology**

Mud rheology represents the heart of the drilling fluid and provides extraordinary support in the case of rig equipment pumping limitation. Also, it plays a significant role of leading to perfect hole cleaning. The phenomenon of the drilling cuttings falling through the fluid because of the effect of gravitational forces in vertical hole is high. If optimum mud rheology of drilling fluid has achieved, that will improve the capability of drilling fluid to carry drilling cuttings across distinct zones such as geopressured, unconsolidated, caving shale, sloughing shale and fractured zones. Also, that will help to provide minimal circulating pressure losses, low potential for differential sticking and low ECD (Equivalent circulating density) across narrow window hole sections.

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- **Cutting size, shape and density**

The size, shape and density of drilling cuttings affect mainly the slip velocity. However, to determine the previous mentioned features of drilling cuttings with a perfect accuracy is impossible. If the formation has shale caving or sloughing shale the cutting density, size and shape will be so difficult to figure out. They are completely different and quite hard to determine them precisely see the figure – 35. In some wells the top sections have clay formation lithology and are very sticky. The shale shakers will be loaded with muddy cuttings accumulations which make it difficult to determine size, shape and density of each particle separately.

Figure 35 Hole Problem Shale Caving. (Taken from the Rig for 16'' vertical hole section).

1.6.2 Factors Affecting Hole Cleaning in Deviated and Horizontal Hole section:

There are several factors affecting the hole cleaning in deviated and horizontal sections. The most important factors are hole angle, cuttings bed, pipe rotation, mud properties and time of circulation. These important factors are extremely relative to each other.

- Angle of inclination.
- Cuttings beds.
- Pipe Rotation.
- Time of circulation.
- Mud Properties.
- Rate of penetration (ROP).
- Flow rate/annular velocity.

- **Hole Inclination**

There are three different zones of inclination in horizontal well, see figure-36.

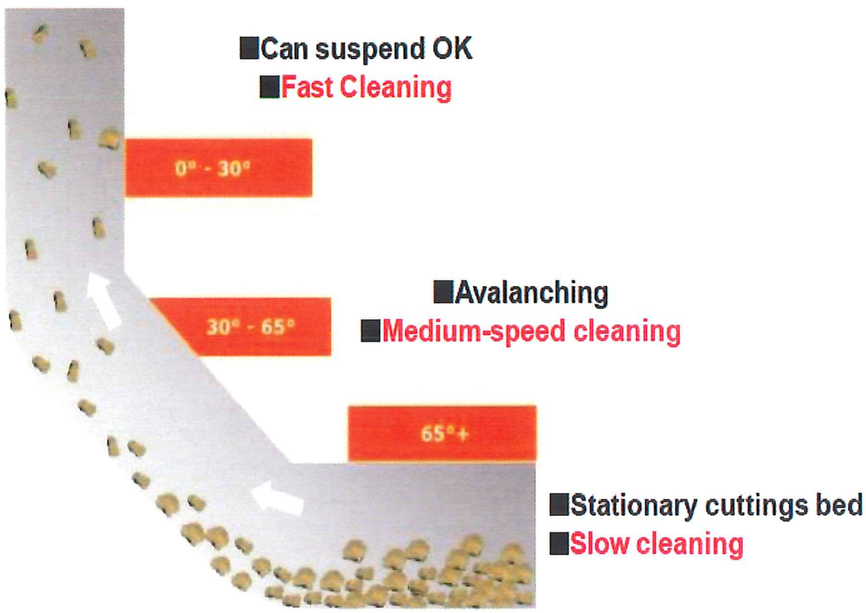

Figure 36 Three Zones Of Inclination.

Mitchel (2001) stated that the moderate angle (30 – 60) deg.

of hole section is the hardest to clean because of the combination of sliding beds, Boycott settling and asymmetrical flow profile see figure-37. Cutting concentration increase dramatically between 30 deg. and 45 deg. and remains relatively constant at higher angles, see figure-38.

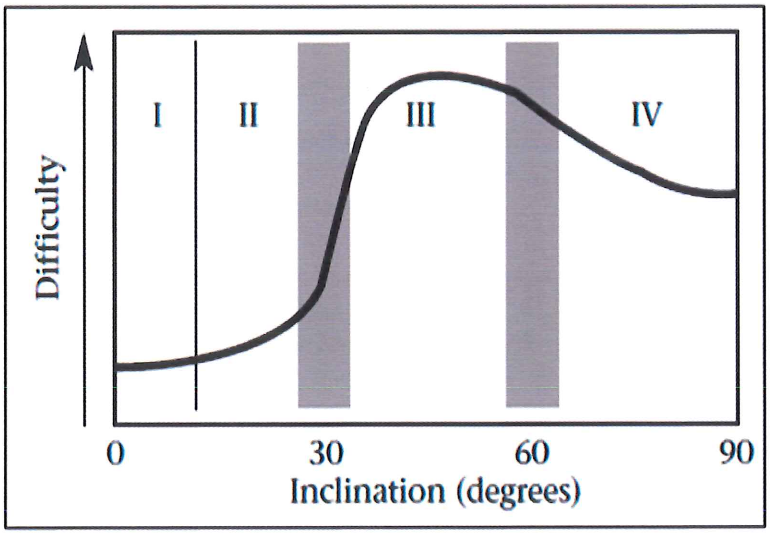

Figure 37 Hole Cleaning Difficulties .Vs. Hole Angle.

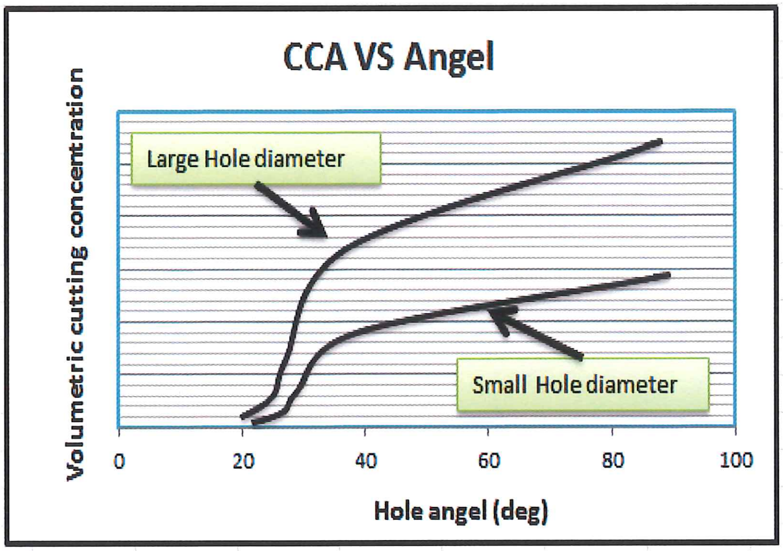

Figure 38 Cuttings Concentration Climbs Rapidly After 30 Deg. (Mitchel 2001)

Mud weight contributes to hole cleaning in higher angles by slowing down the boycott settling effect and by causing cuttings bed to be more fluidized and less compacted. The cutting concentration in the annulus decreases as mud weight increases. Baker and Azar (1985) demonstrated the effect of mud weight on cuttings bed formation. They summarized their findings as follows:

- Cuttings concentration increase drastically between 35 deg and 45 deg at low mud weights but not so drastically at higher mud weights, see figure-39.
- Cuttings bed height reduced with small increase in mud weight at any angle.
- Sliding beds and avalanching of cuttings beds happened less frequently with heavier mud.
- Cuttings beds are more fluidized in heavier mud and thus more easily disturbed.
- Minimum velocity needed to initiate cuttings moving is less with heavier mud.

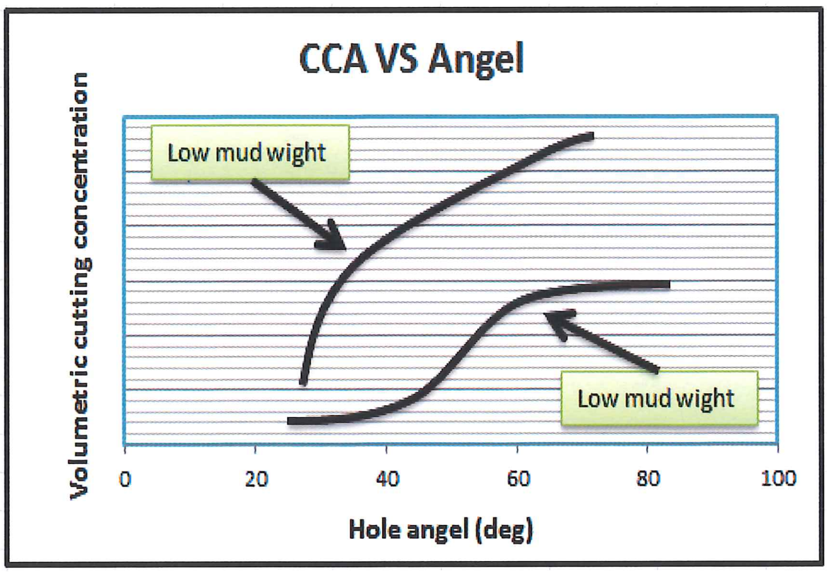

Figure 39 Effect Of Mud Weight On Cuttings Bed Height. (Mitchel 2001).

- **Cuttings Beds**

Cuttings beds are formed during the period of low or no pipe rotation that is the case of directional drilling. Mud properties, flow rate, pipe rotation and hole angle are the major factors that contribute to enhanced cuttings beds removal. Cuttings bed decreases linearly with flow rate due to the eroding to cuttings beds by the annular velocity see figure-40.

High velocity fluid on top of the hole acts like a conveyor belt transporting cuttings out of the hole cuttings will travel so far and then fall off (into low flow zone) due to gravity. The length traveled on the conveyor belt is a function of angle, flow rate, RPM and drilling fluid rheology. Speed of the conveyor belt is a function of flow rate see-figure-41.

Mud properties help the flow rate in removing the cuttings beds by optimizing the plastic viscosity and yield point ratio. Gel strength is also important to suspend cuttings if pump is stoppable. Hole cleaning ratio (HCR) indicates how much cuttings beds are removed by determining their critical height. Minimum transport velocity is also a good indicator to tell about the required velocity to initiate cuttings beds movement see figure-42.

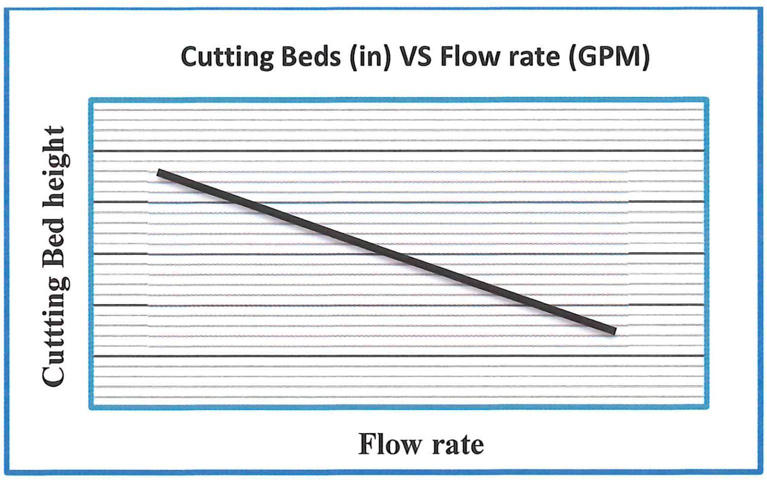

Figure 40 Effect Of Flow Rate On Cuttings Beds. (Mitchel 2001)

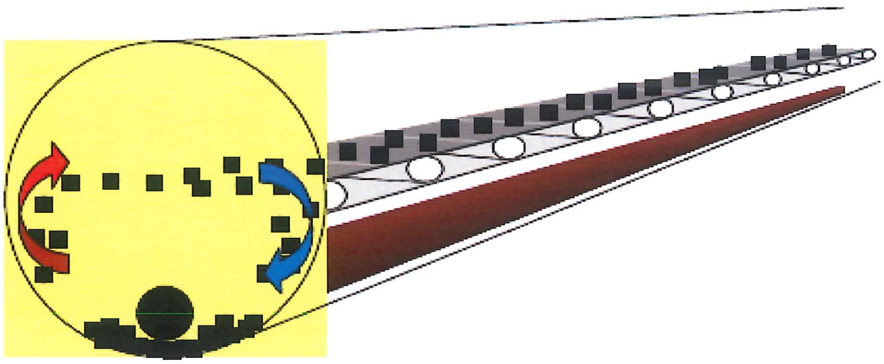

Figure 41 Effect Of High Velocity On Cuttings Beds.

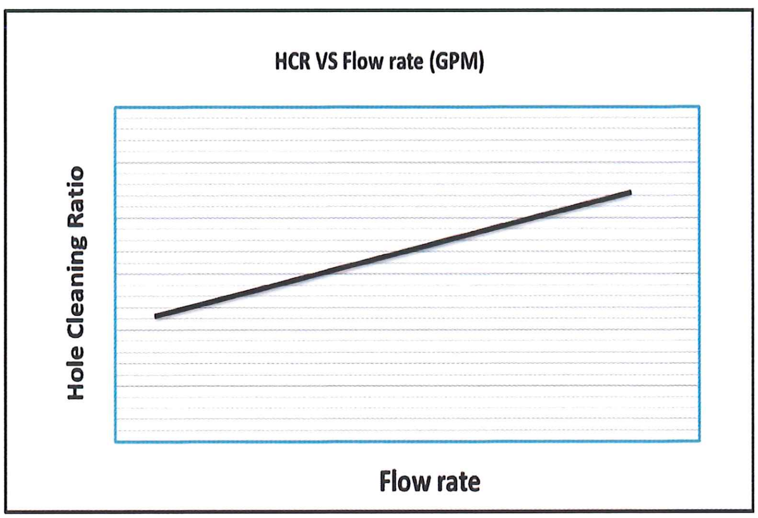

Figure 42 Hole Cleaning Increase Linearly With an Increase in Flow Rate. (Mitchel 2001)

- **Pipe Rotation**

Rotation is the key factor in hole cleaning efficiency for high angle holes. It provides active flow area at the top of hole. Since pipe and cuttings lay along the bottom of hole, the mechanical agitation is required to get cuttings into the fluid flow. The required rotary speed depends on hole size and rate of penetration (ROP).

Pipe rotation can also help remove the semi or have consolidated beds that is part of the drilled formation. The drill pipe drags large proportion of beds by rotation to the top part of the deviated hole of the annulus. The flow rate can help to remove those beds and the hole cleaning can be achieved optimally. This behavior is particularly a possibility for removing sand beds and other non-reactive cutting particles-[Saasen 2007].

In a laminar flow environment, flow rate travels along the top of the hole. Pipe Rotation alone is not sufficient. Critical pipe rotation should lead to have very good hole cleaning performance see-figure-43. It is not actually the pipe rotation (nor the tool joints) that cleans the hole, it is the fluid "film" rotating around the drillpipe, this film is called the "viscous coupling" (Mitchel 2001).

Briefly, the pipe movement itself does not clean the hole, but also, the viscous coupling does as can be seen in figure-44. At low RPM, viscous coupling film is thin and does not add much energy in the system. At medium RPM (say, 100rpm) Pipe begins to walk up the hole a little viscous coupling film gets thicker, but still "thinner" than tool joint upset.

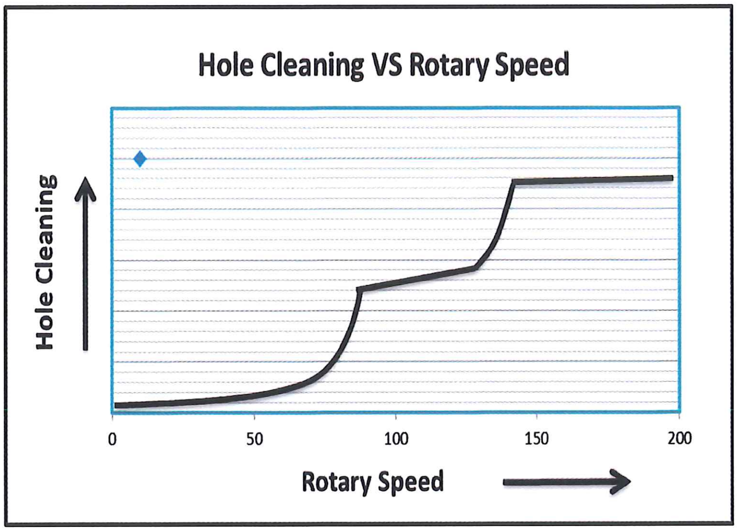

Figure 43 Effect Of Pipe Rotation In Hole Cleaning. (Mitchel 2001)

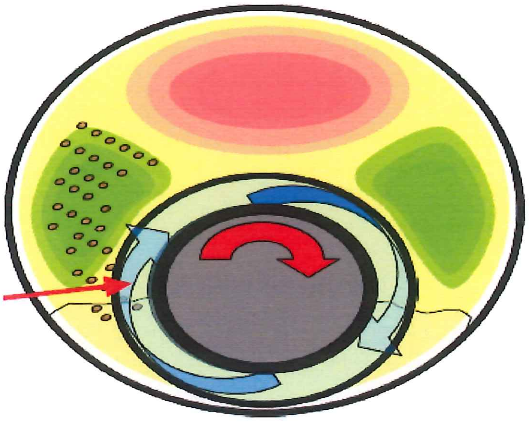

Figure 44 Effect Of Viscous Coupling On Cuttings Accumulation.

- **Time of Circulation**

The time to effectively clean the wellbore increases as the angle increases. Flow rate can remove cuttings even without rotation, but the key here is to have sufficient time of circulation see figures-45 & 46.

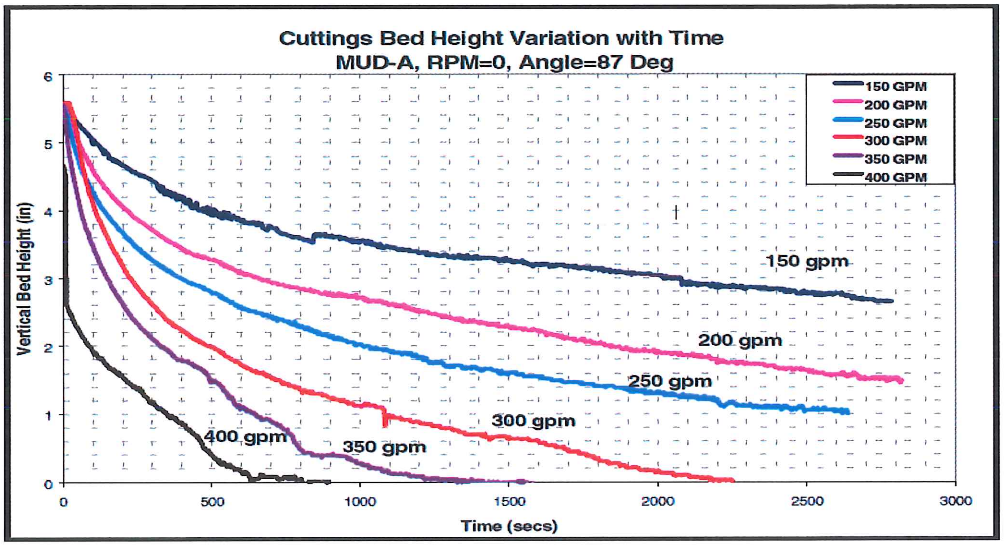

Figure 45 Cuttings Beds Erosion Curve For Variable Flow Rates. (Adari 2000)

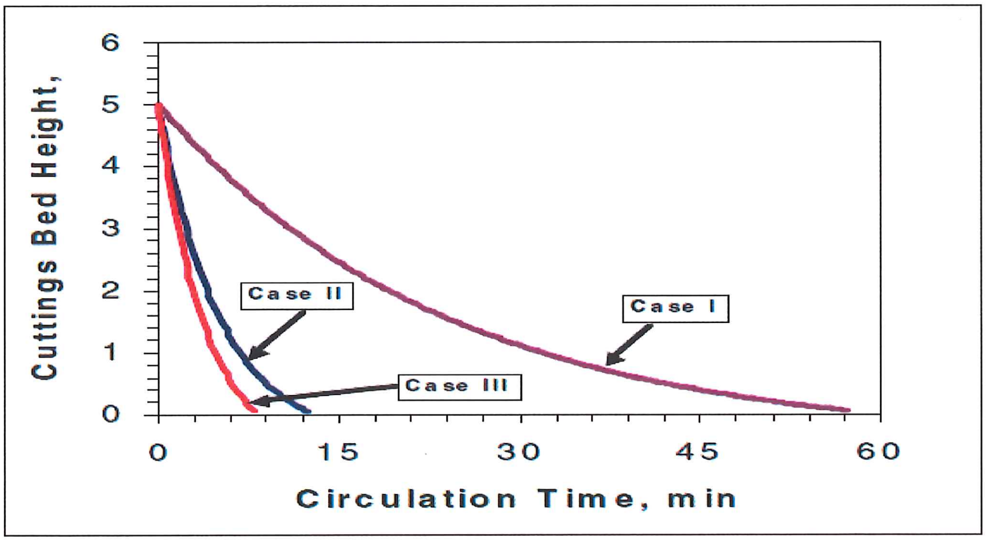

Figure 46 Cuttings Bed Erosion Curves For Required Circulation Time. (Adari 2000)

1.7 Transport Ratio (TR).

The ratio of cuttings or slip velocity to annular velocity is called the transport ratio and it can be used to describe hole cleaning efficiency. Anything that increases the transport ratio, will increase hole cleaning efficiency in vertical and directional wells.

A reduction in slip velocity is one way that the transport ratio can be increased see figure-47. The slip velocity is influenced by the following:

- Size, density and shape of drilling cuttings.
- Rheology, density and velocity of mud.

The larger and heavier the cutting, and the lighter and less viscous the fluid, the faster the cutting will slip through the mud. Much of work and studies were done in vertical wells is to improve hole cleaning efficiency and is aimed to reduce the slip velocity or increasing the annular velocity.

Some initiatives have proposed equations to estimate slip velocity while drilling operations. However, these equations are needed to give precise values in such a complex flow behavior.

Optimum flow rate and drilling fluid parameters have important effect on the hole cleaning since generated drilling cuttings can be removed by applying critical velocity and critical flow rate as well.

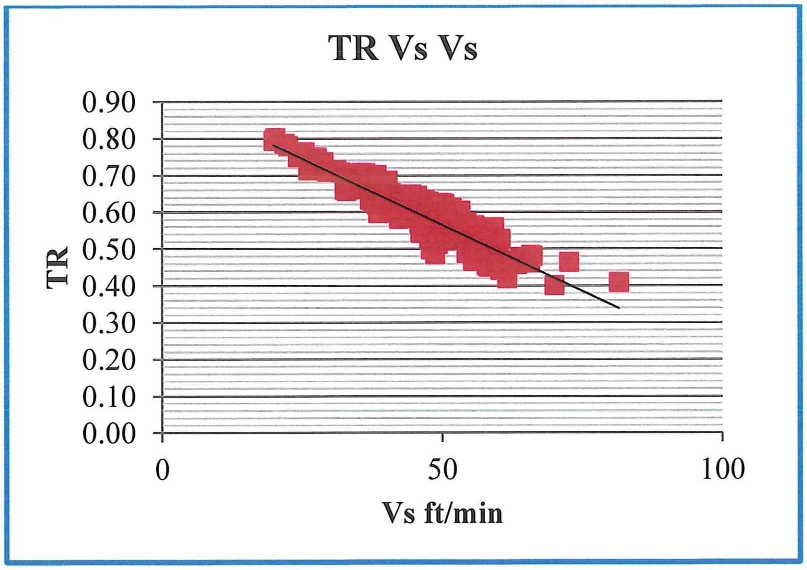

Figure 47 Effect of slip velocity on transport ratio.

The annular velocity which allows fluid in annuli loaded with cuttings to travel up to the surface is a very critical hole cleaning key. As a rule of thumb of some drilling fluid engineers, the annular velocity of drilling mud should be 1.2 times more than the settling velocity to ensure minimum cuttings movement in annulus. The size, shape, and weight of generated drilling cuttings lead to controlling its rate of slipping through circulating drilling fluid. Low rate of shear of viscosity can significantly affect the capability of carrying of mud in the well bore. Drilling mud must have adequate capability of carrying to transport generated drilling cuttings from the wellbore.

1.8 Hole Cleaning Ratio (HCR)

Hole cleaning ratio is the ratio of the height of annular space above the cuttings beds to the critical height of the cuttings bed. Marco Rasi (1994) proposed that if the height of free region above the cuttings bed is greater than the critical bed height, the more pulling through of cuttings bed without circulating. If ratio is greater than one, there will be no problem. If the ratio is less than one then, problems will be expected.

From a study of 50 larger diameter directional wells in North Sea, Rasi (1994) observed that when the HCR was greater than 1.1, no stuck pipe incidents occurred. When the HCR was less than 0.5, stuck pipe always occurred.

As the HCR decreases, the tendency to become stuck increases.

As bed height increases, the annular space above the cuttings bed decreases. The larger the BHA (Bottom Hole Assembly), the smaller the cuttings bed must be to pull through it. In general, over pull tend will increase as the BHA diameter increases. The drill string, bit and stabilizer selection should take these factors into account.

1.9 Transport Index (TI)

Luo, Bern and Chambers (1992) used experimental data from flow loops to determine the optimum parameters of drilling fluids. The following controllable variables were found:

- Flow rate of the mud
- Penetration rate (ROP)
- Drilling fluid parameters
- Flow regime of the mud
- Density of the mud
- The inclination of hole section
- The size of the hole

They also defined some uncontrolled variables such as:

- The eccentricity of the drill-pipe
- Density of cuttings
- Size of cuttings

The effect of the mud weight (MW) was combined together with the (rheology factor) RF and (Angle factor) AF to form a single parameter called the Transport Index (TI).

Transport index must be greater than one. The larger transport index, the more the hole cleaning efficiency. It indicates the minimum flow rate required for each section even if the washout has been induced.

$$TI = RF \ AF \ MW \qquad (1)$$

Where MW is in SG or $\frac{g}{cm^3}$. high inclination of hole section means low value of the angle factor value, hence, the difficulty of hole cleaning will be more, see table-3 and figure-48. The rheology factor (RF) has been found by using PV & YP and the relationship between RF and PV & YP indicates effective hole cleaning. .

From the charts of the factor of rheology, if the YP is bigger than PV the will ensure perfect hole cleaning. AF and RF can be found from **Table-3 and Figure- 49** charts respectively.

Table-4 shows flow rate correction factor for washout to be multiplied by the flow rate pumped for certain hole section.

Hole Angle	Angle Factor
0	2,03
25	1,51
30	1,39
35	1,31
40	1,24
45	1,18
50	1,14
55	1,10
60	1,07
65	1,05
70~80	1,02
80~90	1,0

Table 3 Angle Factor for Different Inclinations (Tobenna 2010)

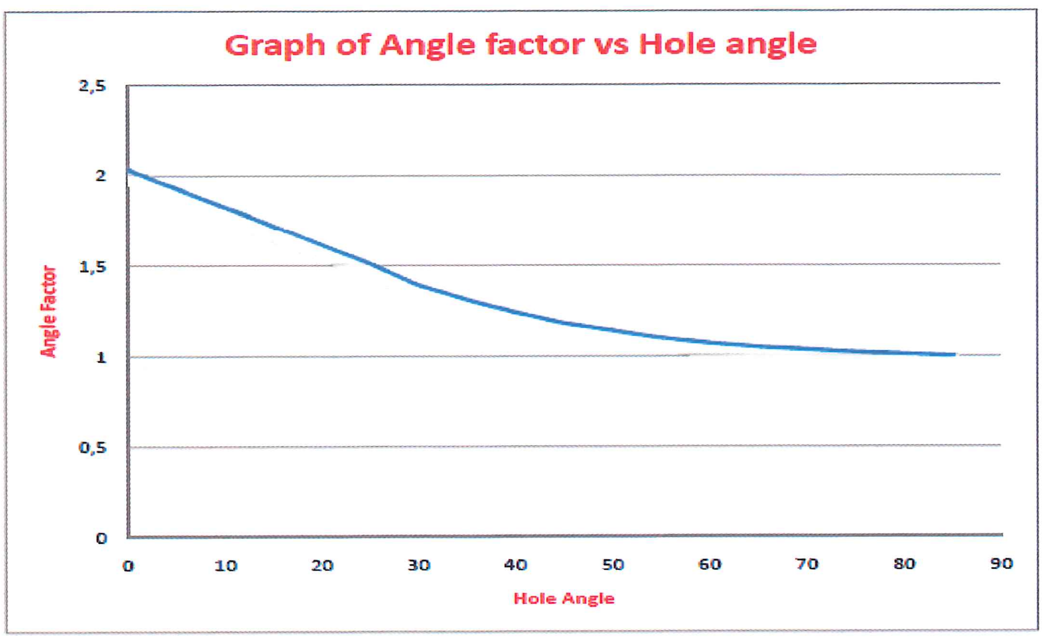

Figure 48 Plot Of Angle Factor Versus The Hole Angle (Tobenna 2010)

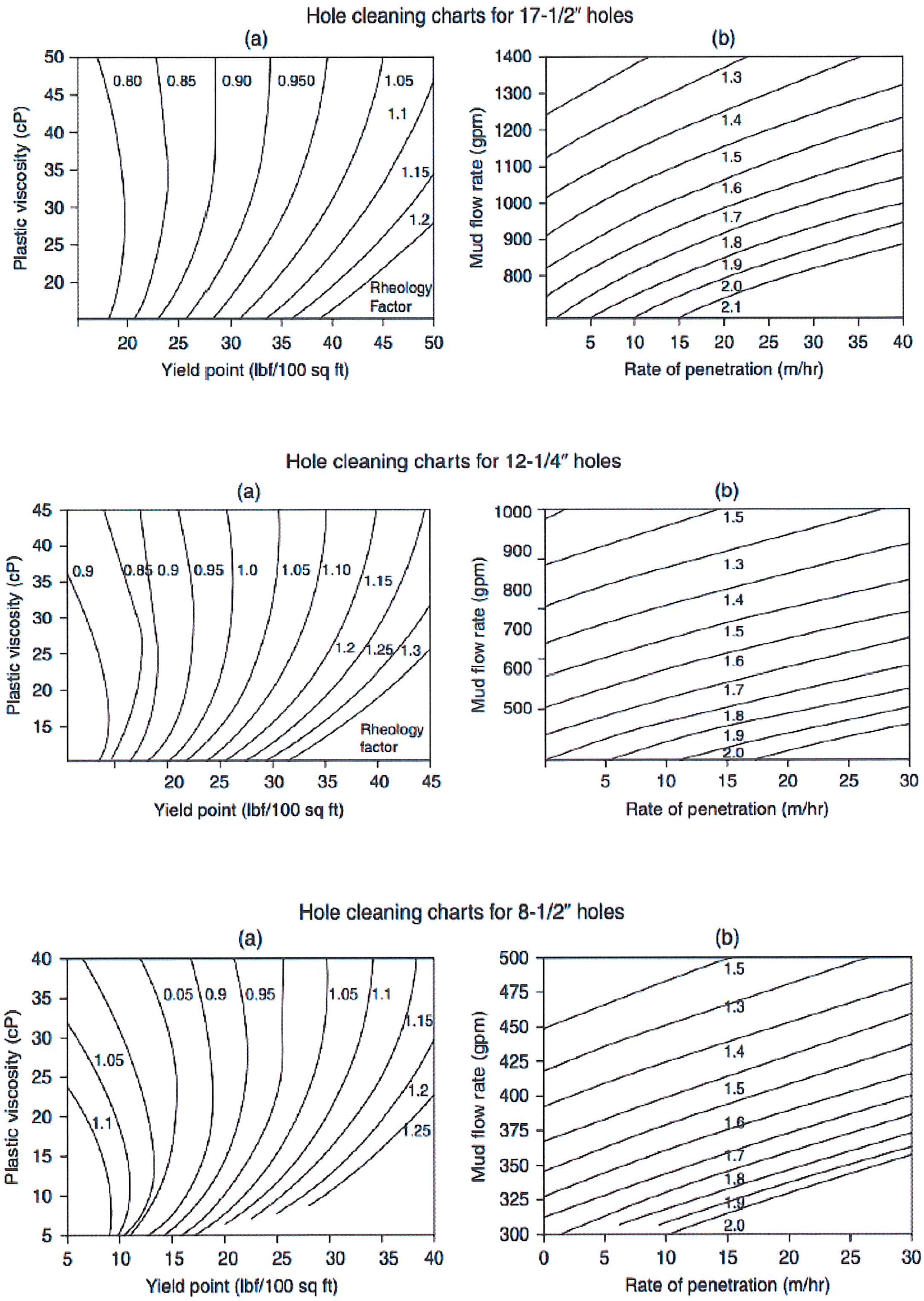

Figure 49 Rheology and Hole Cleaning Charts (Luo 1992)

Flow rate correction factors for washout holes.

8-1/2"		12-1/4"		17-1/2"	
Washout size, in.	α	Washout size, in.	α	Washout size, in.	α
9	1.12	13	1.10	18	1.03
10	1.38	14	1.24	19	1.09
11	1.65	15	1.39	20	1.16
12	1.94	16	1.53	21	1.22
13	2.24	17	1.68	22	1.28
14	2.55	18	1.82	23	1.34

Table 4 Flow Rate Corrections for Washout. (Tobenna 2010).

1.10 Cutting Concentration in Annulus (CCA)

Cutting concentration in the annulus is an effective tool that can indicate how much cuttings generated while drilling, are loaded in annulus. Newitt et al (1955) calculated the cutting concentration in the annulus. The cutting concentration in annulus or cuttings volume has a limit that is not supposed to be exceeded. The limit of the CCA is within the range of 5% to 8 %.

If the CCA exceeds the limit, it can strongly lead to severe hole problems. There are several logical reasons that can explain why exceeding the limit can induce hole problems, see table-5. CCA can help in optimizing the rate of penetration since the limit is known and recognized.

1.11 Carrying Capacity Index (CCI)

The knowledge of the size of cuttings, size of annulus, flow pattern, and down hole fluid properties cannot be determined with high degree of accuracy. Leon Robinson (2004) developed a simple empirical index to help predict hole cleaning. The product of the three most important and influential variables on the transport ratio is equal to a value around 400000 where cuttings are properly lifted to the surface.

Good hole cleaning is indicated when the cuttings have sharp shape edges (Leon Robinson 2004). Round edges indicate that there is tumbling action in the annulus because cuttings are not transported to surface quickly.

The hole cleaning index or ratio is expected to be 1 or greater than 1 for good hole cleaning condition. When a CCI value is 0.5 or less, the cuttings are more rounded and small due to inefficient hole cleaning (longer residence time in annulus).

Good hole cleaning can be achieved by increasing the value of K (consistency index) and annular velocity. This CCI is applicable in Vertical hole sections of inclination from 0 to 25 degrees.

For deviated and horizontal hole section, CCI must be modified. Tobenna (2010) found a relationship between TI and CCI that will enable CCI to be used in horizontal wells. Modified CCI is applicable for the inclination greater than 26 degrees.

Problems	Impact
Increased PV,YP, Gels), and 6 and 3 RPM readings	• Poor cutting transport • High ECDs, • Possible break down of formation and lost circulation
Increased fluids loss/thick filter cake	• Differential sticking • High torque and drag
Slow ROP	• Chip hold down pressure
Increase in density	• Possible break down of formation • Increase dilution and addition of chemicals to maintain proper density
Poor cement displacement	• Channels that allow pressure communication up the wellbore.
Increased abrasion and wear of mud pumps and down hole motors and tools	• Increased cost • Lost time
Increase disposal cost of drilling waste	• Environmental • Health Safety

Table 5 Problems and Their Impact of High Solid Concentration in Annulus.

1.12 Impact of Hydraulics.

Several authors such as Kendall (1960) and Larson (1997) have identified the drilling variables and drilling constraints used in the case of drilling hydraulics optimization. Drilling fluid and bit hydraulics are important subjects for obtaining perfect hole cleaning and optimized drilling rate.

The drilling engineer and drilling rig supervisor must be aware about the effect of drilling fluid hydraulics and bit hydraulics. The knowledge and interpretation of the drilling hydraulics are the keys of acquiring the optimization. Understanding the circulating pressure or mud pump pressure that includes pressure loss of surface equipment, pressure loss of drilling string, pressure loss of mud motor, pressure loss of bit and pressure loss of annulus, is critical.

Additionally, understanding the other terminologies and analyzing them such as total flow area of nozzles (TFA), jet velocity of nozzles (Vn), pressure loss of bit (dPb), Hydraulic horsepower of bit (HHP), hydraulic horsepower of bit per square inches (HSI), jet impact force (Fj) and drilling specific Energy of bit (DSE) are so valuable to be well known.

A comprehension of hydraulics will help clean hole optimally, utilize maximum power that is available to drill hole and know the effect of mud properties on pressure losses.

1.13 Total Flow Area (TFA) and Jet Velocity (Vn)

It is the total area of nozzles of the bit. It depends on the number and the size of nozzles. It can increase the pressure loss across the bit and improve the jet velocity, see figure-50. The optimum size and number of nozzles can assist in hole cleaning and optimize the drilling rate significantly. That will be very helpful to increase the hydraulic horsepower and jet impact force. The less total flow area available, the more jet velocity can be achieved see-figure- 51. However, the drilling engineer or drilling foreman must take in to the consideration the LCM (loss circulation materials) to avoid nozzles plugging. Jet velocity has an effective impact on hydraulics horsepower of bit per square inch (HSI). It can increase it significantly to ensure optimized drilling rate by ensuring optimum hole cleaning see figures-52 &53

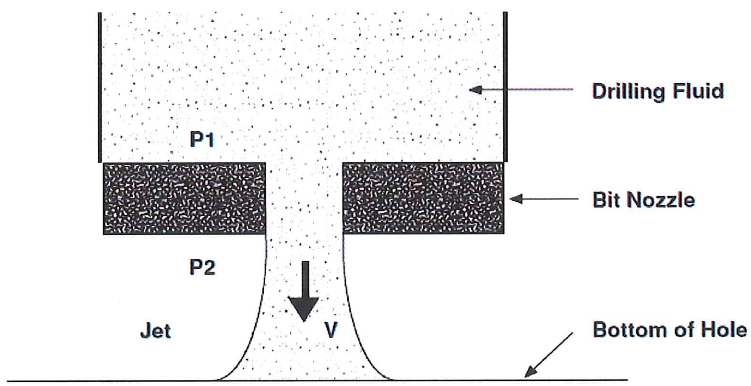

Figure 50 Discharge Throgh a Nozzel (Drilling Hriott Watt 2012)

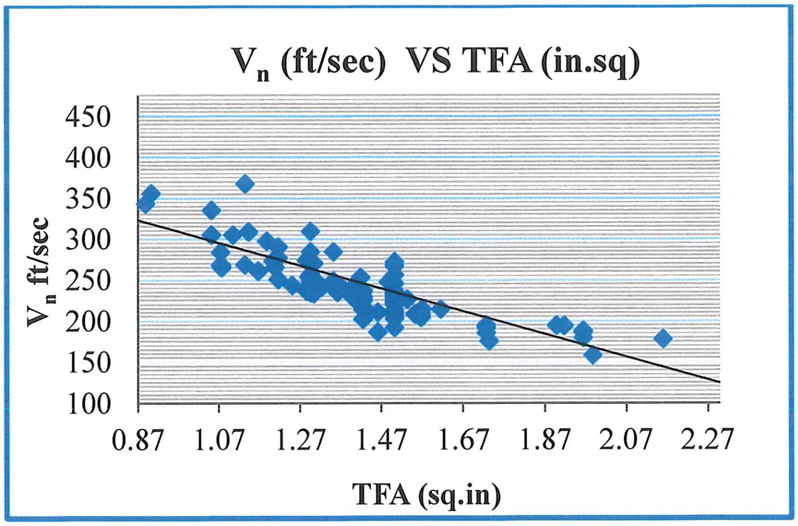

Figure 51 The Effect of Total Flow Area of Bit Nozzle on Jet Velocity Through Nozzles.

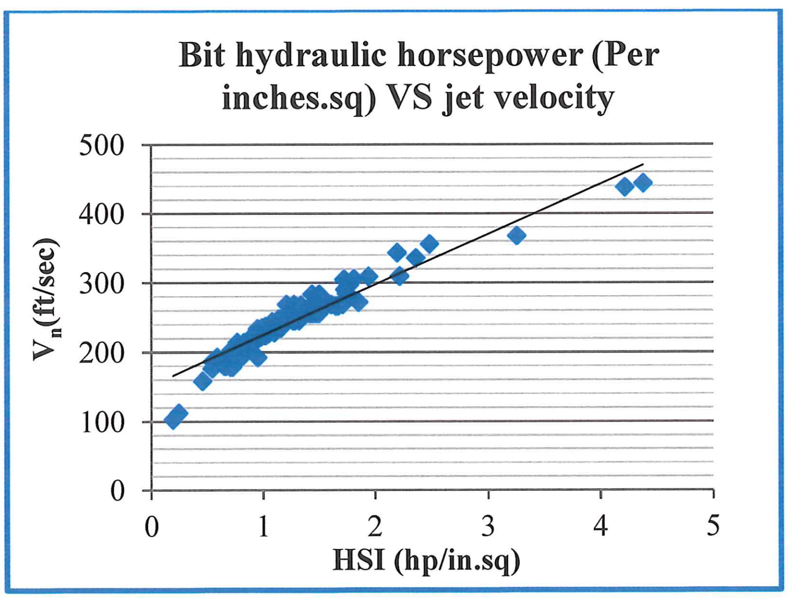

Figure 52 The Effect of Jet Velocity on HSI.

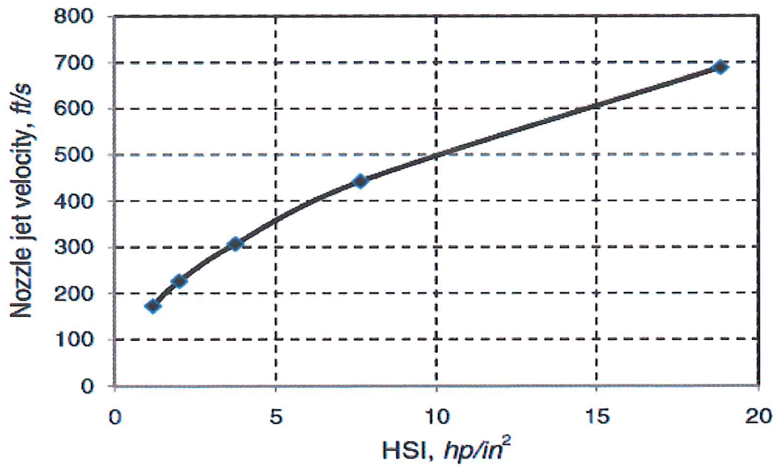

Figure 53 Nozzle Jet Velocity for Different HSI. (Ali 2014)

1.14 The Pressure Loss Across Bit (dP_b)

Knowledge of the circulating pressure or mud pump pressure or rig pump pressure as well as the pressure across the bit can effectively contribute to drilling hydraulics optimization. Leon (2010) has defined fundamentally the pressure and stress as the energy per unit volume. In 1983 M. Ramsey proposed a new nozzle coefficient (1.03) and, independently by Warren (1989).

There is a known nozzle coefficient (0.95) which means the pressure loss across the nozzle is more than the available kinetic energy by 110%. The new proposed nozzle coefficient of Leon (2010) explains that 94% of kinetic energy can cause the pressure loss. The pressure can be increased smoothly by changing nozzle size and nozzle coefficient, see figure-54 & 55.

The pressure across the bit can increase the hydraulics horsepower, that will lead to more hole cleaning by jet impact force (F_j) and more drilling rate by hydraulic horsepower per square inch (HSI). See the effect of bit pressure on (F_j) & HSI as show in figures -56 & 57.

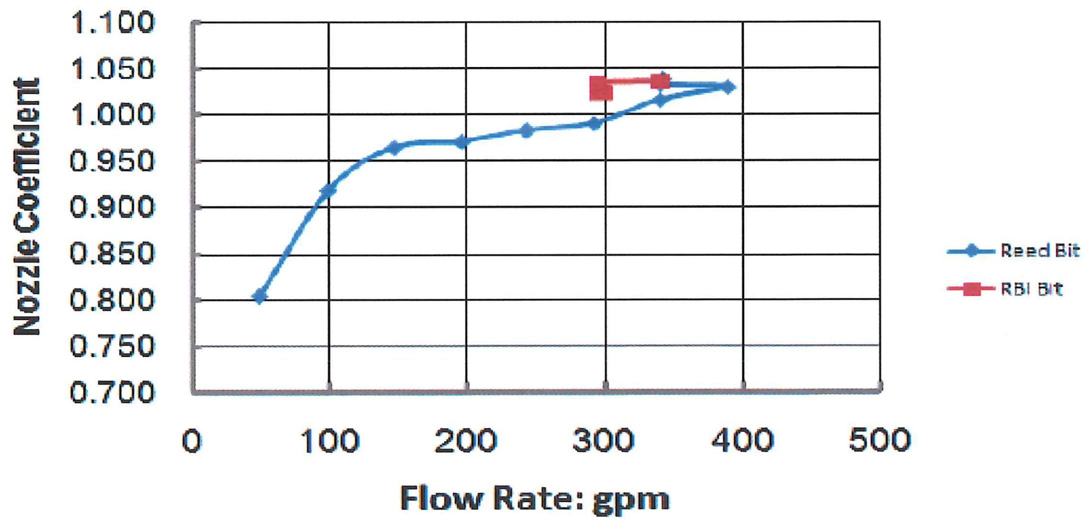

Figure 54 Nozzle Coefficient Change With Flow Rate. (Leon 2010)

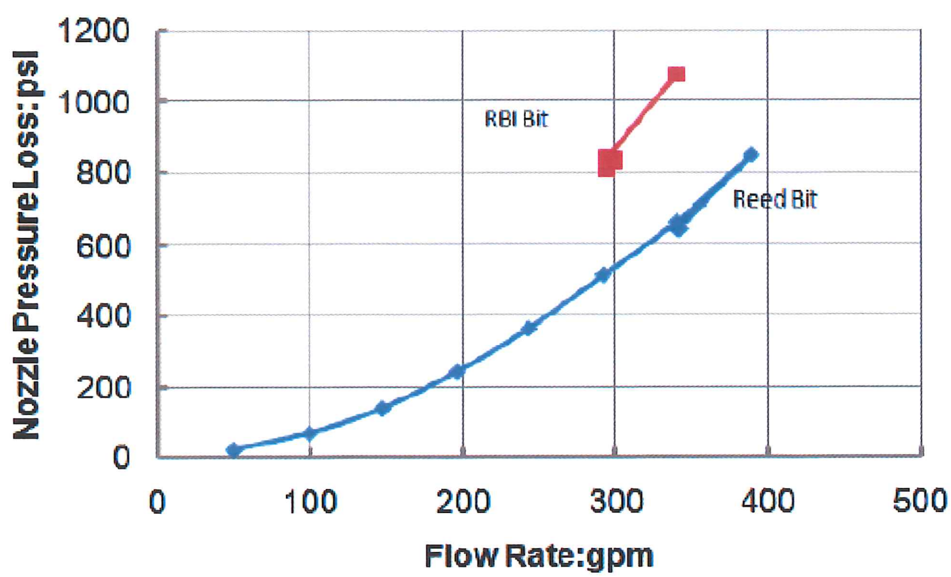

Figure 55 Increases in Pressure Losses through Nozzles (Leon 2010)

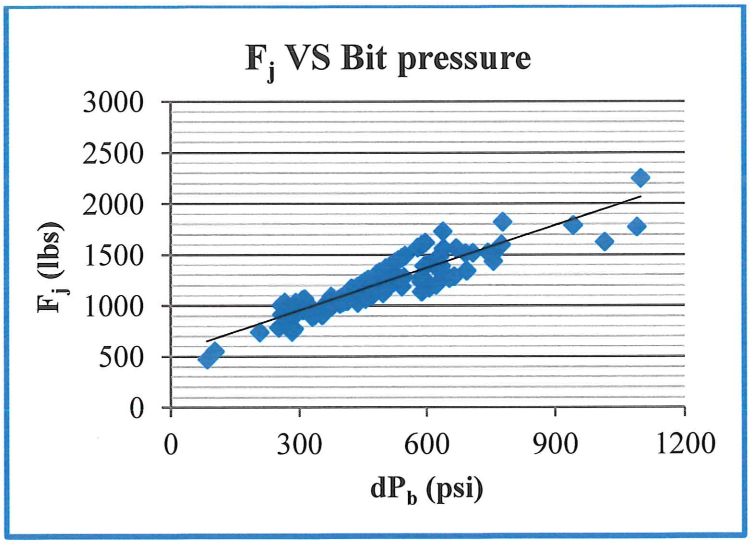

Figure 56 Effect of bit pressure in jet impact force.

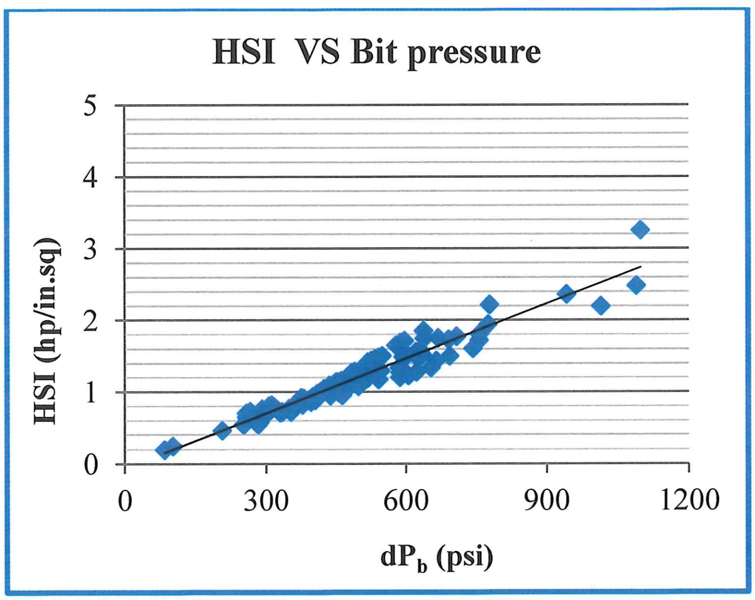

Figure 57 Effect of bit pressure on HSI.

1.15 The Hydraulic Horsepower of Bit (HHP), Hydraulic Horsepower of Bit per Square Inches (HSI), and Jet Impact Force (F_j).

Early published work on hydraulics optimization focused on increasing bit hydraulic properties: bit hydraulic horsepower, bit jet velocity and jet impact force, examples include Kendall (1960) and Moore (1958) studies. It is very critical to reduce the pressure loss of the circulating system and increase pressure loss across bit to have sufficient hydraulics horsepower which effectively can transport drilling cuttings to surface and improve the rate of penetration.

The main factor is the optimum flow rate. The mud rheology parameters are the key of the optimum and influenced flow rate. If the HHP is low at bit and does not have enough hole cleaning support, the drilling will be reduced due to the bit balling or bottom hole balling (happens usually with the grinding action of hard formation bits).

The drilling rate will decrease even with increasing weight on bit (WOB) unless the HHP is improved see figure-58. HSI indicates how much HHP can be applied in one square inch of area of hole section. It improves the drilling rate and shows how to push the bit more for drilling.

The HHP and Fj have a valuable relationship and are important factors for drilling rate and hole cleaning respectively. They can influence the drilling efficiency and impact the cost effectively as can be seen in figures 59 & 60.

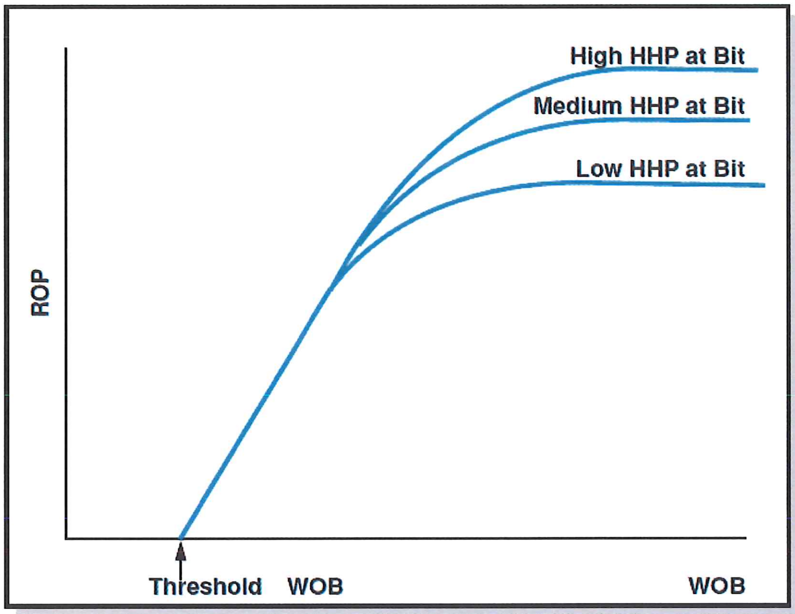

Figure 58 Impact of HHP on ROP at Given WOB. (Drilling Herriot Watt 2012)

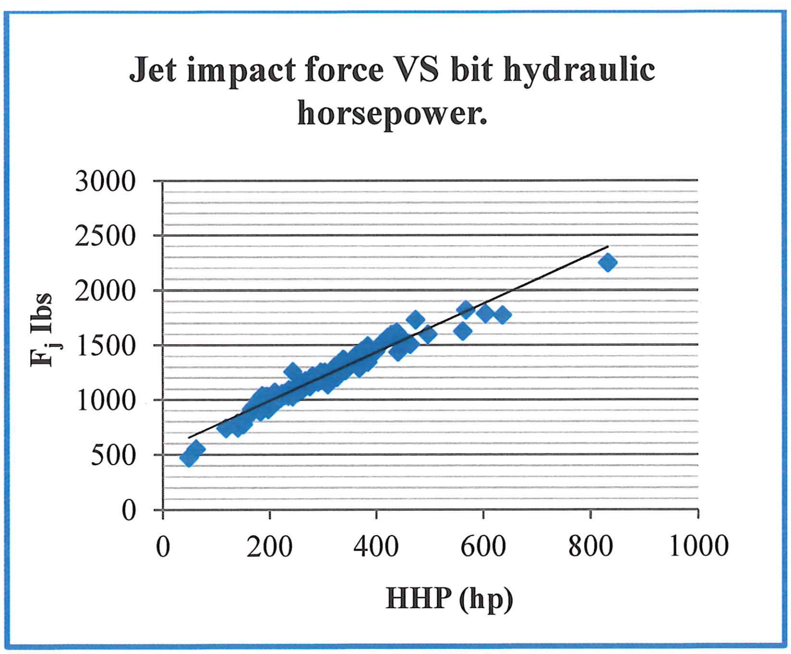

Figure 59 The Relationship between HHP and Fj.

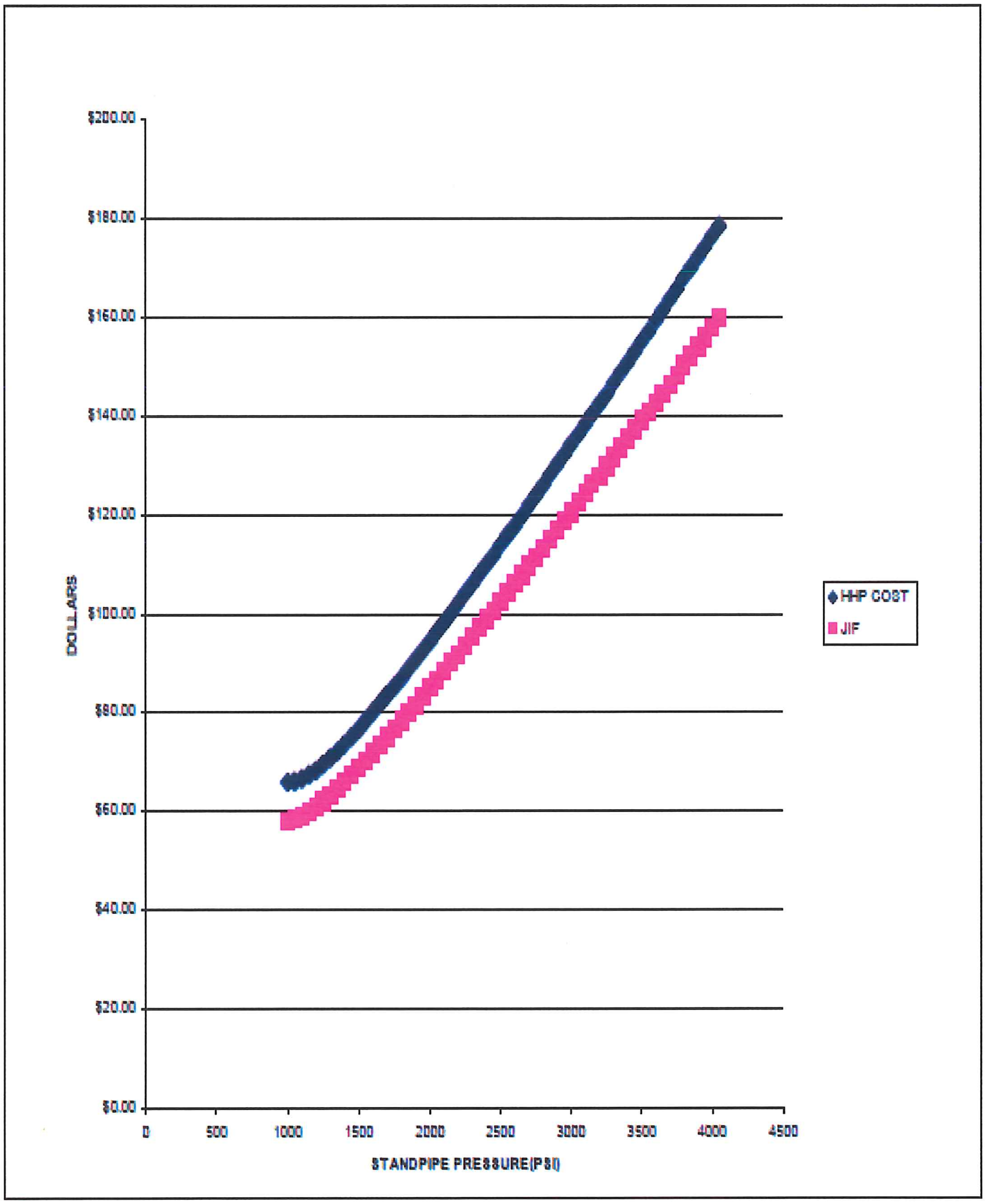

Figure 60 The Impact of HHP & Fj on The Cost of Drilling. (James 2003)

1.16 Mechanical and Drilling Specific Energy (MSE &DSE)

Generally it indicates how the drilling is efficient. Specifically, it is the needed energy for removing a unit volume of rock. To obtain excellent performance of drilling, mechanical specific energy is decreased in order to have optimum drilling rate. To minimize MSE or DSE the drilling parameters such as (WOB, Torque, ROP and RPM) must be controlled.

MSE is a ratio. MSE demonstrates the relationship among the required energy to destroy the rock and rate of penetration. The ratio is constant for a given rock

Teal (1965) has derived the concept of MSE as follows:

$$MSE = \frac{Input\ energy}{out\ ROP} \qquad (2)$$

$$MSE = \left(\frac{480\ TRQ\ RPM}{{D_B}^2\ ROP} + 1.273\frac{WOB}{{D_B}^2}\right) \qquad (3)$$

DSE or MSE is utilized to elect the required WOB and RPM that can increase the drilling rate till the point that ROP starts to deviate from linearity to flounder point and that indicate more hole cleaning efficiency is required to be achieved. It is useful to relate DSE or MSE to the drill off curve see figure-61.

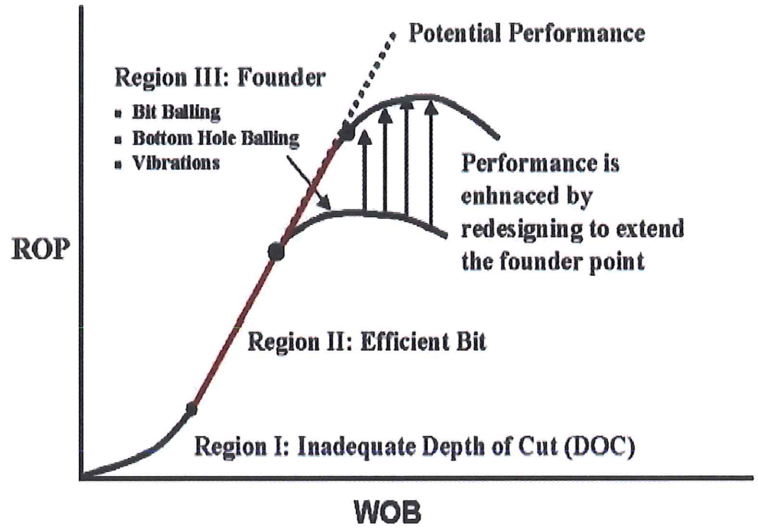

Figure 61 Relationship between ROP and WOB (Dupriest 2005)

- **Drilling Specific Energy**

The original equation developed by Teal (1965) for MSE has been altered by Miguel Armenta (Miguel 2008) to include a bit hydraulic horsepower. The number 1,898,000 in Miguel equation is a unit conversion factor. The ratio of bit hydraulic power HHP of bit and bit area (HHP/AB) is the bit Hydraulic power per square inch HSI.

The connection of DSE and ROP was tested for distinct drilling parameters such as (WOB, and HSI). DSE vs. ROP for variable WOB values for all the tests that display different curves according to the WOB as can be seen in (Figure- 62). All the curves have analogous shape viewing three main sections: (1) High DSE and low ROP representing incompetent drilling; (2) low DSE and high ROP which designate effective drilling; (3) A transition zone from section 1 to section 2 in amongst these two regions. (Armenta 2008).

Field data were selected to estimate DSE using Armenta's equation (2008) to recognize incompetent drilling situation. The DSE and ROP both were plotted first against depth to recognize any specific configuration as shown in figure- 63.

To display the effect of the hydraulic term or the HSI, again DSE was plotted vs. ROP but this time the data is classified according to the HSI. The WOB curves are preserved on the plot to make a linking.

Figure-64 displays that all the data with HSI between 0.5 hp/in^2 and 1.7 hp/in^2 are found on the incompetent drilling section (Section 1: high DSE and low ROP) for their specific WOB. On the other hand all the data with HSI between 5.8 hp/in2 and 7.9 hp/in2 are on the competent drilling section (Section 2: low DSE and high ROP).

It is shown from his equation (Armenta) that the bit hydraulic is the main thing to change from incompetent drilling when the WOB is persistent. When growing HIS, not only are the cutting removed faster underneath the bit, but also the bit cutting configuration is reserved clean to break new rock more successfully. The parameter Lambda (λ) is a dimensionless bit hydraulic factor depending on the bit diameter as can be seen in figure-65.

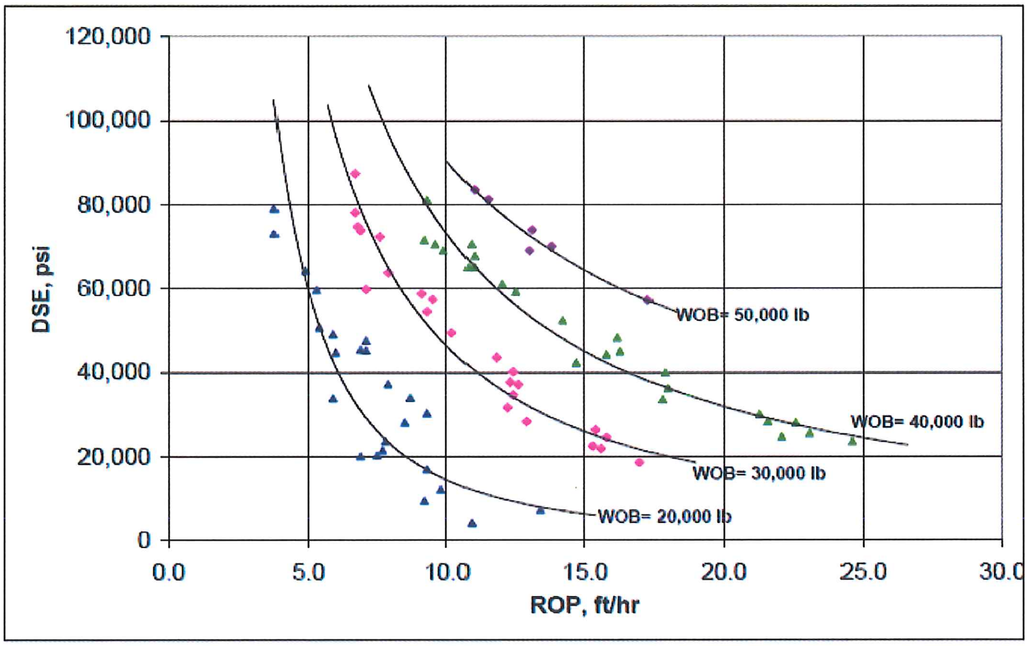

Figure 62 DSE vs. ROP with Experimental Data Grouped According to the WOB (Miguel Armenta 2008)

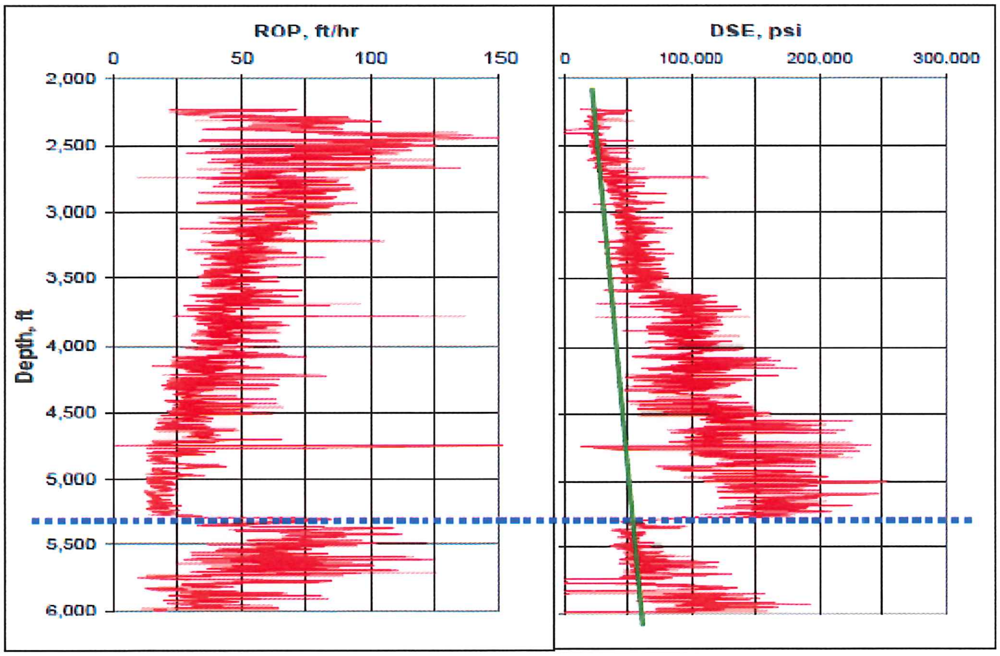

Figure 63 ROP and DSE vs. Depth for Field Data (Miguel Armenta 2008)

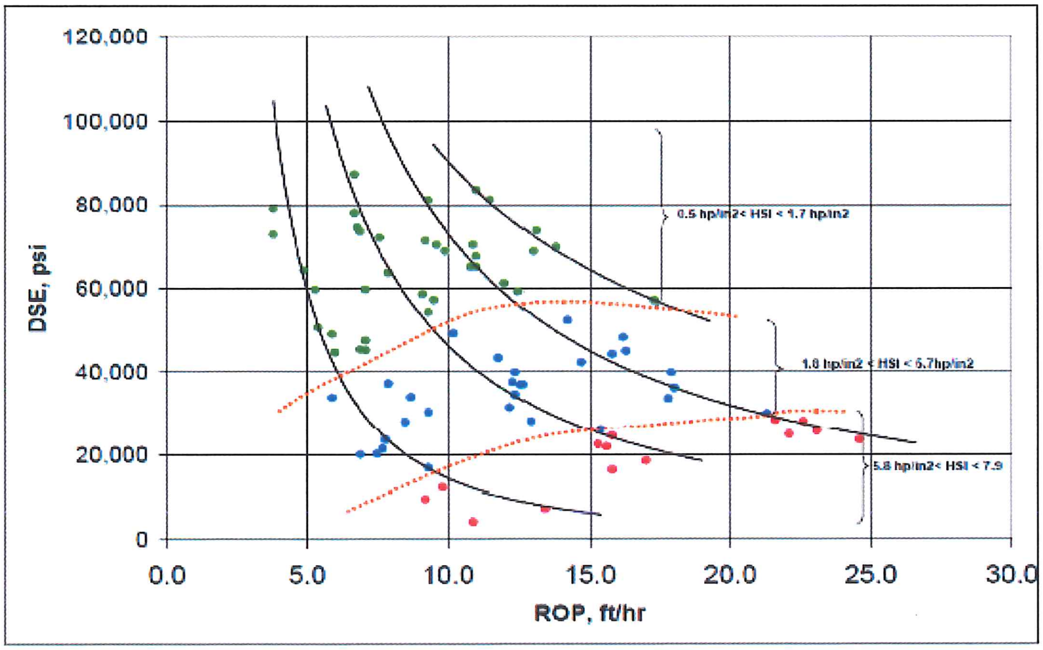

Figure 64 DSE vs. ROP with Experimental Data Grouped According To the His (Miguel Armenta 2008)

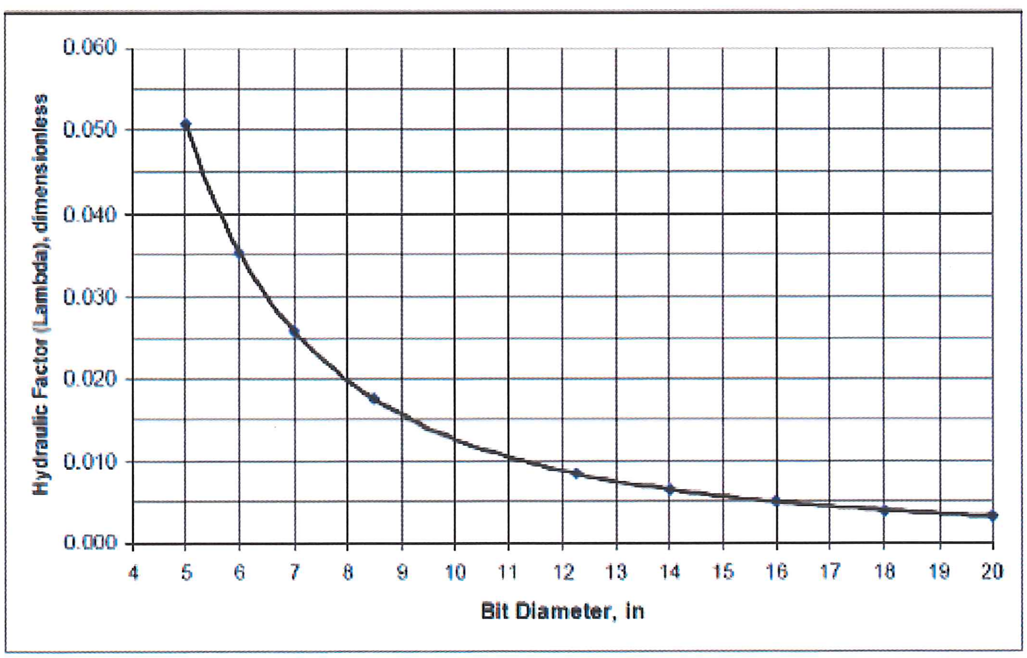

Figure 65 Hydraulic Factor Vs Bit Size (Miguel Armenta 2008)

CHAPTER 6
LITERATURE REVIEW

Many references related to hole cleaning contain good ideas to enhance the hole cleaning, but several of them are just based on theory and lack proper experimental data and not feasible in drilling operations.

Several correlations were developed to improve hole cleaning practices. The most important correlations include Moore (1977), Larson (1997) and Malekzadah (2012).

Many methods were used to enhance the hole cleaning. The methods were applied in the field successfully with acceptable results. The recognized and critical methods like sensitivity analyses, mud rheology, drill pipe rotation and statistical methods was introduced by Siavomir (1962), Okrajini and Azar (1992), Rasi (1994) and Kian (1997).

Naeg (1998), Walker (1999), Connell (2005) used tools such as coil tubing jetting tool while performing wiper tripe, Cutting flow meter & new external profile on drilling equipment. The most efficient tools were vectored annulus cleaning system and real time monitoring system.

Brown (1985), Terry (1993) and Ford (1994) did several experimental and theoretical studies. Their objective was to improve the results of hole cleaning. For example, factors studied include required annular velocity in annulus, mud properties, mud system and frictional pressure losses.

Several models have been used to optimize hole cleaning. Some of them are great models but they are limited to certain applications. The most famous models are Lyoho (1987), Ford (1988), Adari (2000), King (2007), Bilgues and Amannullah (2010).

Luo (1994), Hemphill (1999) and Ivan (2013) developed charts and some field applications to be used to have better hole cleaning. These charts and applications when applied showed limited improvement but not recommended in all drilling operations.

Some additives were used the mud to increase hole cleaning efficiency. Zamora (1996), Kenny (1996), Frank (1998), and Power (2000) have used foams, polymers, fibrous LCM (Loss Circulation materials), Sweeps, High density sweep & ester-based drilling fluid system.

Murer (1986), Hertzberg (1996), Bizanti and Blick (1986) modified the design of PDC (polycrystalline diamond cutter) to come up with new configuration that can help to increase horsepower and jet impact force of the bit. They developed some computer models such as MTV (minimum transport velocity), Simulation & 3 D modeling).

We can classify the references used to study hole cleaning as listed in Table-6:

- Correlations.
- Rheology properties.
- Bit design.
- Some field Applications.
- Experimental and Theoretical studies.
- Computer models.
- Charts.
- Adding Chemicals or other mud system.
- Programs software models.
- Sensitivity Analyses methods.
- Mud Rheology models.
- Bit Hydraulics Analysis models.
- Method of Drill Pipe rotation.
- Coiled-Tubing jet tool.
- Devices & tool.

Technique	Author	Year
Correlation	Moore, Larson, Salehi And Malekzadah,	1977,1997 & 2012
Methods	Siavomir, Okrajni ,Azar,	1962, 1986, 1992, 1994, 1996, 1997,
	Ozbayoglu, Saasen, Sorgun & Svanes	
	Ogunrinde, Kian, Sifferman, Rasi, Sanchez, Sarasin,	
	Saasen Chakwal, Ravi, Wilde, Hertzberg, & Thor	1998, 2003, 2006, 2007, 2009 &2010
Design	MAURER And Hertzberg	1986 & 1996
Fluid Dynamics	Bizanti, And Blick	1986
Models	Lyoho, Ford, Adari, King, Bilgesu & Amnullah	1987, 1988, 2000, 2007, 2010
Tools	M. Naeg, Walker, Boulet, Connell	1998, 1999, 2000, 2001, 2005
Real Time	Martian , Adewale	2003, 2015
Charts	Luo	1994
Fields Results	Erhu, Guild, Hemphill, Ivan	1994, 1995, 1999, 2013
Experimental	Brown, Terry, Ford	1985, 1993, 1994
Materials	Zamora, Kenny, Frank, Power,	1993, 1996, 1998, 2000, 2003, 2008, 2012
	Stephane, Charles, Kjosene, Ahmed, Erik	

Table 6 Hole Cleaning References.

The main focus in this research will be on cutting concentration in the annulus, carrying capacity index or ratio, mud rheology, transport ratio and drilling specific energy. Therefore, the following literature review will be focused on the most relevant methods and /or known to work well.

Williams and Bruce (1951) have done experimental study on shape of drilling cuttings which caused poor transport efficiency that was caused by parabolic shape of laminar velocity regime, that makes the shape of drilling cutting flat due to the effect of unbalanced acting forces of drilling mud. As a result of that, they changed the regime of drilling fluid in annulus to laminar.

Newitt et al (1955) calculated the cutting concentration in the annulus based on annular velocity, and they concluded that percentage of cutting concentration should not be more than 5 %.

$$CCA = -\frac{1}{2}\left(\frac{Vann}{Vs} - 1\right) + \sqrt{\frac{1}{4}\left(\frac{Vann}{Vs} - 1\right)^2 + \frac{Vann}{Vs} Vc/(\frac{Q}{7.48})} \qquad (4)$$

$$Vann = \frac{24.5\ Q}{H^2 - OD^2} \qquad (5)$$

$$Vc = \frac{ROP}{60}\left(\frac{\pi}{4}\frac{H^2}{144}\right) \qquad (6)$$

$$Vs = Av\ x\ (1 - TR) \qquad (7)$$

$$Vann - corrected = Av\ x\ (1 + S\frac{Vs}{Av}) \qquad (8)$$

CCA=cutting concentration; %. Should be < 5%

V_{ann}= annular velocity; ft/min

V_c =critical velocity; ft/min

V_s = Slip velocity; ft/min

$V_{ann\text{-}corrected}$ = Corrected annular velocity; ft/min

ROP= rate of penetration; ft/hr

H= hole diameter; in

OD= Drill pipe diameter; in

TR= Transport Ratio; %

Mitchell (1955) suggested a new method to calculate cutting concentration in annulus. It accounts for cessation of circulation during connection and circulation which occurs prior to a connection but after drilling has ceased. This latter circulation is called Pre-Connection Circulation time.

$$\frac{1}{CCA} = 1 + \left(1 - \frac{OD^2}{OH^2}\right)\left(\frac{Vdp\ ann - Vs}{LDP}\right)\left(\frac{60L}{ROP} + \frac{Vs}{Vdc - ann\ - Vs}Tc\right) \tag{9}$$

CCA: Cutting concentration in Annulus

V_s: Average drill cutting's slip velocity; ft/min.

L: length of one drill pipe (usually 30 ft); ft.

T_c: Time for one connection; min

L_{DP}: Length of drill pipe: ft.

$V_{dp\text{-}ann}$: Annular velocity across Drill pipe: ft/min.

$V_{dc\text{-}ann}$: Annular velocity across drill collar: ft/min.

Mitchell (1955) stated in his book (Advanced Oil Drilling Engineering) that API developed a new model to calculate the cutting concentration in annulus by using the transport ratio.

$$CCA = \frac{ROP\ OH^2}{1472\ GPM\ TR} \tag{10}$$

Where, ROP is rate of penetration (ft/hr), OH is the hole section size (in), 1472 is conversion factor, GPM is the flow rate (gal/min) and TR is the transport ratio.

Hopkin (1967) tested more than 2000 dynamic particles carrying tests with 8 feet and 4 ½ inches diameter vertical tubes with 13 types of drilling muds and 52 particles of different shapes and sizes. He used flow regimes (laminar, transitional and turbulent) to circulate the particles from the bottom of the tube to the top. In addition, mud march funnel viscosities ranged from 26 to 1000 seconds/qt. He found a relationship between Slip velocity with march funnel, yield point and mud weight. The graphs were plotted as can be seen in figures - 66, 67 & 68.

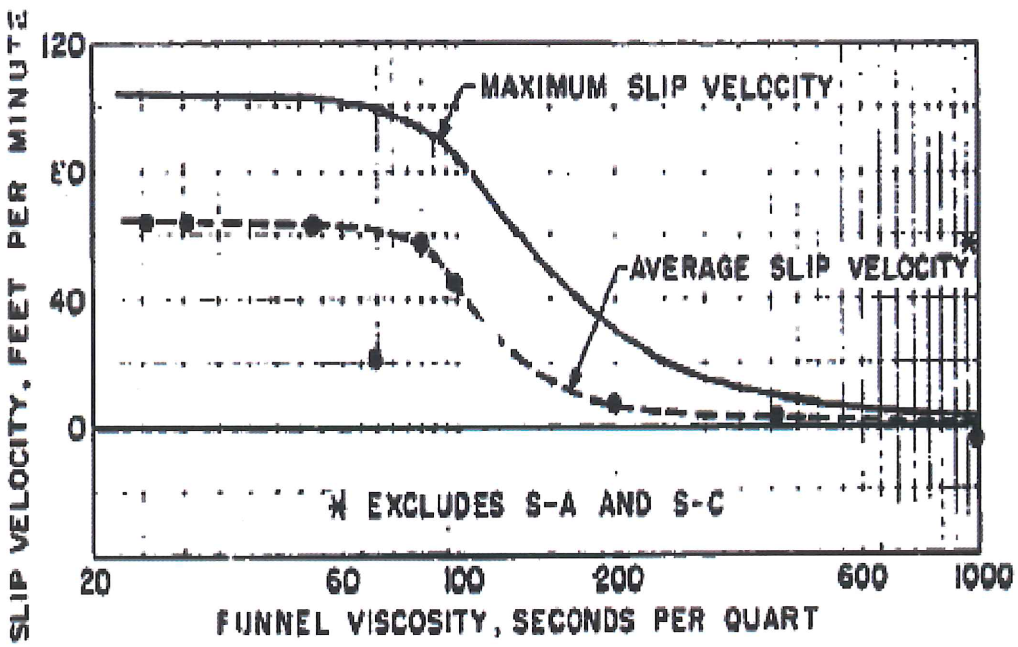

Figure 66 Slip Velocity and Funnel Viscosity. (Hopkin 1967)

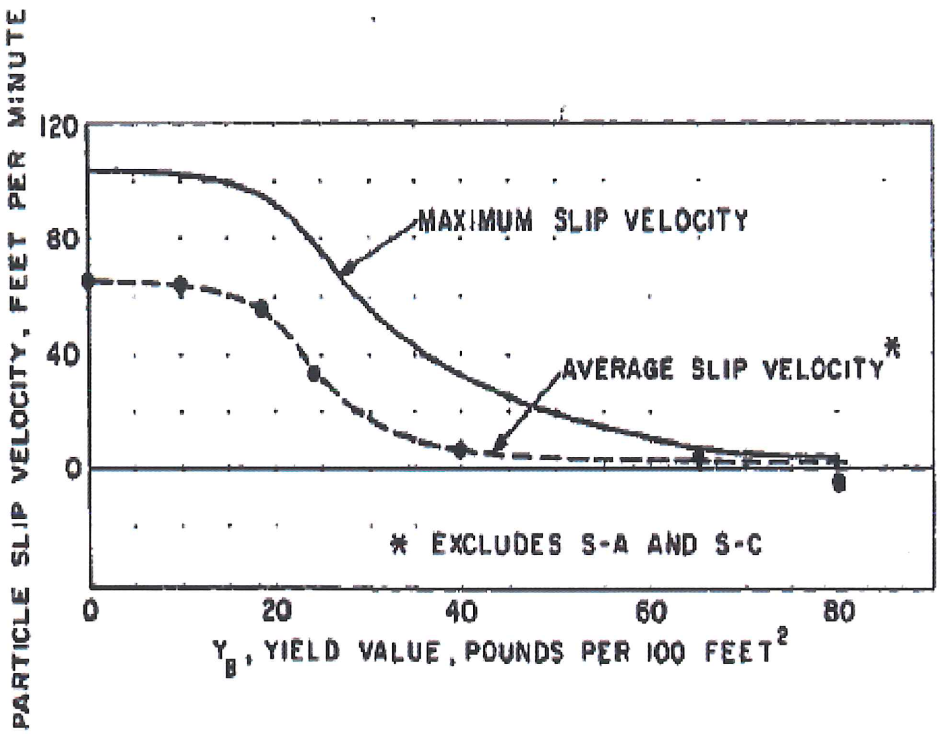

Figure 67 Slip Velocity and Yield Point. (Hopkin 1967)

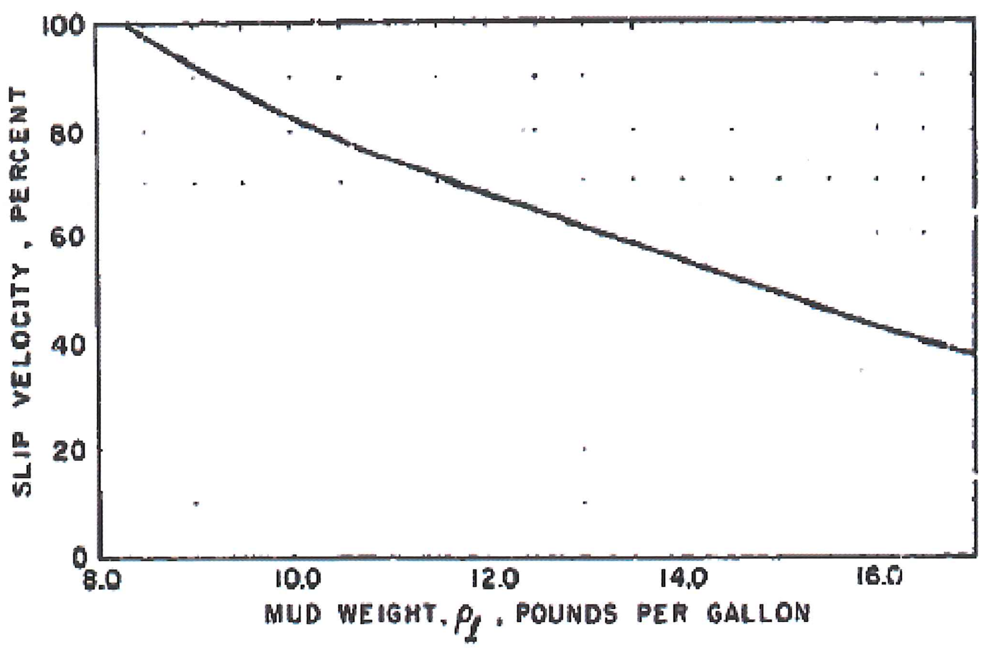

Figure 68 Slip Velocity and Mud Weight. (Hopkin 1967)

Sifferman et al (1974) conducted experimental tests on generated cuttings in annuli for three mud systems having low, medium, and high rheological properties. The results of the test are presented in figure-69. The higher the yield point, the higher the transport ratio. He also, published transport ratio collected with an annular flow model with a 12-inch outer steel tube and various diameter inner tubes. The model was about 100 feet long. He defined transport ratio as:

$$TR = \frac{Vf - Vs}{Vf}, \qquad (11)$$

TR= transport ratio,

V_f= Mud annular Velocity; ft/min

V_s= Solid free settling (slip) velocity; ft/min

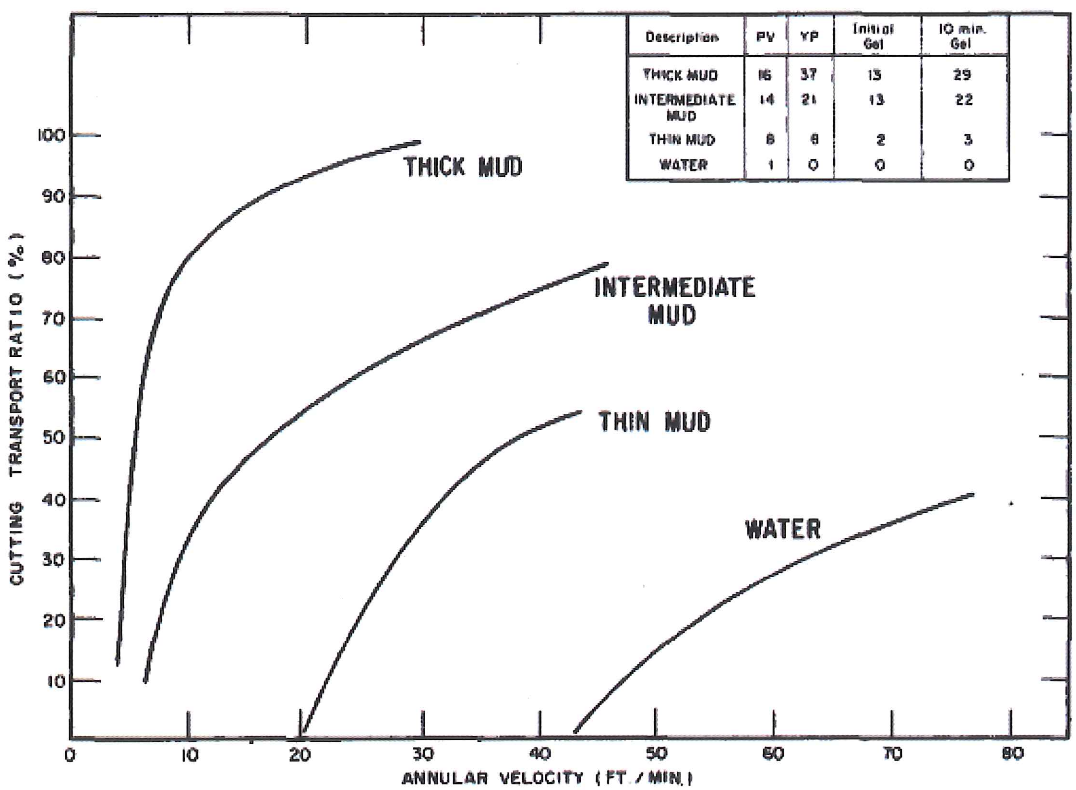

Figure 69 The Effect of Annular Velocity of on Transport Ration for Different Mud Systems. (Sifferman 1974).

Zeidler (1974) figured out that 164 ft/min of annular velocity in two fields in Canada was necessary to clean holes with clear water.

Hussaini and Azar in (1983) have found that drilling mud rheology had significant impact on transport of drilling cuttings just if annular velocity is less than 120 ft/min. Because if the annular velocity is more than 120 ft/min in gauged hole, it will influence mud rheology. Hence, that will affect transport ratio only in washout zones of the wellbore. Hussaini and Azar's tests were dealing with drilling fluids that were using apparent viscosities ranging from 20 - 40 cP. Obviously, Hussaini and Azar's study is inapplicable to low values of apparant or effective viscosities.

Robinson and Morgan (2004) developed a new term which is called the Index of Carrying Capacity (CCI) to predict hole cleaning efficiency in vertical hole sections.

$$CCI = \frac{MW\ K\ Av}{400{,}000} \tag{12}$$

MW= the mud weight in PPG,

A_v= Mud annular Velocity; ft/min

K= the consistency index, equivalent cp

K= $511^{(1-n)}(PV + YP)$,

$PV =$ Plastic viscocity ; cp

YP= yield point ($lb/100ft^2$)

$n = 3.32 \log\ ((2PV + YP)\ /\ (PV + YP))$

Tobenna (2010) developed a new model of rheology factor by using carrying capacity index. This model can be used in vertical and horizontal wells. The model formulations that he derived analytically is for predicting hole cleaning irrespective of the hole angle.

$$CCI = (\frac{K\ SG\ Af}{3585\ Aa}) \qquad (13)$$

K: consistency index, equivalent cp

K= $511^{(1-n)}(PV + YP)$,

PV: Plastic viscocity ;

YP: Yield point $(lb/100ft^2)$

$n = 3.32 \log((2PV + YP)/(PV + YP))$

A_a: Annular Area; ft^2.

SG: Specific gravity.

The drilling specific energy (DSE) that was modified by Armenta (Miguel 2008) to include a bit hydraulic-related term on the (MSE) correlation. It was modified more to simplify the calculations by **khamis (2013)**. **Armenta (2008)** presented the term next to the minus side to capture the effects of drilling hydraulics. The method and the outcome is like Teale (1965) as the last newly presented term is very small in value. The value for **λ** in Armenta charts was 0.005.

$$\boldsymbol{DSE = \frac{WOB}{A_{Bit}} + \frac{120\pi\ RPM\ TRQ}{A_{Bit}\ ROP} - \frac{1{,}98\ 10^4\ \lambda\, HHP\ bit}{A_{Bit}\ ROP}} \qquad \textbf{(14)}$$

λ= bit hydraulic factor, HHP = bit hydraulic horse power ،AB= Area of Bit.

Mohan et al. (2009) offered a new link to recognize incompetent drilling cases by using MSE. Hydro Mechanical Specific Energy (HMSE) was presented which covers hydraulics and mechanical specific energy. The HMSE equation will be of value for the duration of both preparation and effective stages of choosing drilling parameters and also assistance in boosting them.

Tuna and Evren (2010) established a model to enhance drilling parameters during drilling operations such as WOB, RPM to find supreme ROP and hence minimize the cost per foot and generally drilling cost. The model established used real field data which will be used for calculating ROP as a function of existing parameters. The study proved that ROP could be anticipated at exact levels, based on historical drilling trend.

Khamis (2013) modified the drilling specific energy equation (DSE) that had been derived by Armenta (2008). The objective of the modification was to find the correlation of hydraulic factor of all sizes of bits. He used DSE to optimize ROP by selecting improved drilling parameters using (Particle swarm Optimization) PSO technique.

$$DSE = \frac{4\ WOB}{\pi {D_B}^2} + \frac{480\ \ RPM\ TRQ}{{D_B}^2\ ROP} - \frac{3{,}189{,}335\ HHP_B}{{D_B}^4\ ROP} \tag{15}$$

HHP = Bit hydraulic horse power ، A_B= Area of Bit.

- **Particles swarm optimization.**

Particle swarm optimization (PSO) can be defined as computational manner which will enhance a given problem by performing many trials and tests to optimize a proposed solution that is relevant with a special measure of quality. The optimization process of PSO begins to have a huge number of proposed solutions that called particles, and then having these particles searched based one preferable and simple mathematical law for position of particles and velocity. The movement of proposed solution are caused through the local best-known position. Then aimed toward best matching position in search space and finally enables movement of the swarm direct to the best proposed solutions.

PSO is basically attributed to Kennedy, Eberhart and Shi, (Kennedy, 1995) and (Shi, 1998), and was first intended for estimating the behavior of society , (Kennedy, 2001), as a representative style of the movement of organisms in a flock of bird or school of fish. The algorithm was simplified and it was noticed to be doing enhancement. The book by Kennedy and Eberhart, (Kennedy, 1997), describes many aspect of philosophy of PSO and intelligence of swarm. An extensive survey of application of PSO is done by Poli, (Poli, 2007) and (Poli, 2008).

PSO can do a few or no assumptions about the problem that is being enhanced and makes very large spaces of proposed solutions. However, PSO cannot ensure an exact solution is ever found. Especially, PSO does not use the gradient of the problem which is being optimized, that means PSO does not ask for the enhancement of problem to be different as is required by classic optimization methods such as gradient descent and quasi-newton methods. PSO makes also the use of optimization of problems that are partially irregular, noisy, change over time, etc.

- **The Penalty Approach.**

Penalty approach can be described as a method for converting a controlled optimization problem into a categorization of unconfined problems. After dividing into a sequence of unconstrained optimization problems, the penalty approach is introduced based on the degree of constraint violation as well as reflecting the requirements for design variables.

Some penalty methods were presented by Al-Mutairi, Dhaifallah, Christian Grossmann, and Vu Kim Tuan (2000). These methods include logarithmic obstructions, and exponential penalties approaches which outline a constantly differentiable prehistoric and lane and applied to linearly constrained convex problems. Richard, Nocedal, and Waltz (2008) have contributed to the development of a new discussion of penalty techniques for nonlinear optimization. The possibility of penalty parameter adjustment is introduced by these methods via controlling the degree of linear practicability produced for every reiteration. The updated penalty plan is shown in the context of sequential quadratic programming and sequential linear-quadratic programming methods by the utilization of trust regions to promote convergence.

Some penalty methods are introduced for the purpose of solving optimum Dirichlet control problems by the steady-state and time-needy Navier-Stokes equation by Holt and Ravindran (1998).These methods are compared numerically in two versions with the addition of generalized penalty methods to the time-reliant case. Both approaches of semi and fully discrete approximation for time-dependent Dirichlet control problems are mentioned and executed. Also, existence of reported numerical results for solving both the steady-state and the time dependent Dirichlet control problems.

Based on the literature review, that Cutting Concentration in Annulus (CCA) and Carrying Capacity Index (CCI) are the most important tools to be considered to ensure optimum hole cleaning, optimized ROP performance and effective mud properties.

CHAPTER 3

3.1 Problem Statement.

Having reviewed the previous research and studies, it can be concluded that previous studies have focused on different methods, correlations and models.

The key element in a successful drilling project is to have efficient hole cleaning, which depends on implementing perfect drilling mud rheology and applying best drilling practices. The usage of Carrying Capacity Index (CCI) will enable us to optimize the mud rheology even if rig limitations exist. CCI and CCA are effective tools to predict hole cleaning in hole sections because the knowledge of the size of cuttings, size of annulus, flow pattern, and down hole fluid properties cannot be determined with high degree of accuracy by TR, HCR and TI.

The application of CCI alone will not help in optimizing ROP to the desired limit. In addition, there must be enough energy in drilling fluid to enable the drilling fluid to carry the solids out of the hole which is carrying capacity of mud. It can be represented by lifting capacity of mud. Therefore, controlling Cutting Concentration in Annulus (CCA) combined with CCI will ensure having perfect hole cleaning facilitating achievement of optimized ROP with using DSE that can be minimized by selecting optimum drilling parameters.

Establishing of effective hole cleaning in different hole sections can help eliminate wiper trips, reaming trips, pumping of sweeps and increase ROP performance significantly, leading to reduction in cost of well drilling. The ultimate medium for cutting transport during drilling is via the circulation of drilling fluid for that reason optimum flow rate of mud pump and mud rheology must be taken into account.

No previous work was found that simultaneously monitors Cutting Concentration in Annulus (CCA) and Carrying Capacity Index (CCI) with DSE and models how they can be controlled to ensure optimum hole cleaning, effective mud properties and ultimately optimized ROP performance.

<u>The problem statement can be summerized as follows:</u>

- Low ROP performance can be due to poor hole cleaning which can increase wiper trips, reaming trips, pumping of sweeps leading to increase in cost of well drilling.
- The knowledge of the size of cuttings, size of annulus, flow pattern, and down hole fluid properties cannot be determined with high degree of accuracy using TR, HCR and TI.
- Cutting Concentration in Annulus (CCA) alone cannot inform us about the drilling mud properties.
- The application of CCI alone will not help in optimizing ROP to the desired limit.
- No previous work has been found in the open literature that simultaneously monitors Cutting Concentration in Annulus (CCA) and Carrying Capacity Index (CCI) and models how they can be controlled to ensure optimum hole cleaning, effective mud properties and ultimately optimized ROP performance.

3.2 Objectives

The main objective is to develop a new hole cleaning model based on monitoring and control of Cutting Concentration Index (CCI) and Cutting Concentration in Annulus (CCA) with using DSE to establish efficient hole cleaning in challenging hole sections, leading to optimum drilling rate performance.

Specifically:

- Develop effective hole cleaning model by utilizing the carrying capacity index and the cutting concentration in annulus.
- Observe the drilling rate change after achieving optimum hole cleaning.
- Confirm optimum drilling rate using Drilling Specific Energy (DSE).
- Selecting optimum drilling parameters using Particle Swarm Optimization (PSO).

CHAPTER 4
Model Development

4.1 Methodology

The approach of this research work is to study well drilling parameters and mud rheological properties. The data will be analyzed to determine the effect of mud properties and drilling parameters on hole cleaning and ROP performance in certain hole sections. The data selected are from the same hole size, formation type and mud type.

In the first phase, the relationship between mud rheological properties and CCI will be evaluated to determine how strong they are. The data will be screened and filtered to capture the significant CCI and mud rheological properties. Graphs of the various drilling mud parameters and CCI will be plotted against each other will assist in identifying the relationship between them. Table 7 shows field data to be collected which will be screened to pick the required parameters such as (Flow Rate, String Rotation speed, Torque, Weight on bit, Footage, Hours spent to drill hole section, Flow area of nozzles, Mud Weight, Mud Funnel Viscosity, Plastic Viscosity, Initial gel strength, Final gel strength, and Yield Point).

Phase I: Collecting and Screening Field Data to identify the Significant Parameters.

Items	Terms	Parameters	Acronyms	Unit
1	Pumping Rate	Drilling	GPM	Gal/min
2	String rotation speed	Drilling	RPM	rev/min
3	Torque	Drilling	TRQ	ft-Ib
4	weight on bit	Drilling	WOB	Ib
5	Footage	Drilling	FTG	ft
6	Hours spent to drill hole section	Drilling	T	hrs
7	Flow area of nozzles	Hydraulics	TFA	in^2
9	Mud Weight	Rheology	MW	PPG or PCF
10	Mud Funnel Viscosity	Rheology	FUN. VIS	CP
11	Plastic Viscosity	Rheology	PV	CP
12	initial gel strength	Rheology	GI	Sec
13	Final gel strength	Rheology	GF	Min
14	Yield Point	Rheology	YP	$\frac{Ib}{100}ft^2$

Table 7 Drilling Parameters and Mud Rheology from Collected Data.

In the second phase, the effect of mud properties and drilling hydraulics will be studied. Table 8 shows mud properties and drilling hydraulics such as (Ratio of plastic viscosity over Yield point, Ratio of Yield point over plastic viscosity, Flow behavior Index, Consistency Index, Apparent viscosity, Effective viscosity, Annular Velocity, Critical Velocity, Slip Velocity, Bit Pressure Loss, Jet Velocity of nozzles, Bit Horsepower, Bit Horsepower per Bit Area, Jet Impact Force, Annular Pressure Loss, Equivalent Circulating Density, Drilling Rate, Transport Ratio, Cutting Concentration in Annulus (Newttis's Method), Cutting Concentration in Annulus (API) and Cutting Concentration Index,

Phase II: Study the effect of Mud Rheological Properties and Drilling Hydraulics.

Items	Terms	Parameters	Acronyms	Units
1	Ratio of plastic viscosity over Yield point	Rheology	PV/YP	Unit less
2	Ratio of Yield point over plastic viscosity	Rheology	YP/PV	Unit less
3	Flow behavior Index	Rheology	n	CP
4	Consistency Index	Rheology	K	CP
6	Apparent viscosity	Rheology	µapp	CP
7	Effective viscosity	Rheology	µeff	CP
8	Annular Velocity	Hydraulic	Vann	ft/min
9	Critical Velocity	Hydraulic	Vc	ft/min
10	Slip Velocity	Hydraulic	Vs	ft/min
11	Bit Pressure Loss	Hydraulic	Pbit	Psi
12	Jet Velocity of nozzles	Hydraulic	Vj	ft/sec
13	Bit Horsepower	Hydraulic	HHPbit	HP
14	Bit Horsepower per Bit Area	Hydraulic	HIS	HP/in^2
15	Jet Impact Force	Hydraulic	Fj	Ib
16	Equivalent Circulating Density	Hydraulic	ECD	PPG or PCF
17	Depth Of Cut	Drilling	DOC	in
18	Drilling Rate	Drilling	ROP	ft/hr
19	Transport Ratio	Hole Cleaning Indicator	TR	%
20	Cutting Concentration in Annulus (newttis's)	Hole Cleaning Indicator	CCA	%
21	Cutting Concentration in Annulus (API)	Hole Cleaning Indicator	CCA	%
22	Cutting Concentration Index	Hole Cleaning Indicator	CCI	%
23	Consistency Index and flow behavior index	Rheology	K^n	CP

Table 8 Calculated (Drilling Parameters, Mud Rheology Parameters & Drilling Hydraulics).

Phase III: Optimizing Hole Cleaning and Rate of Penetration in Hole Section (Hole Cleaning Model)

In the Third phase, the data and the resulting relationships revealing the best performance will be used to develop a model that can help ensure hole cleaning efficiency and optimized drilling rate.

The results will be used to develop an efficient hole cleaning and optimized drilling rate model in vertical, directional and horizontal wells that will enhance the performance significantly. In addition, it can be used as a tool that can guide drilling engineers to implement optimum performance by using CCI, CCA and DSE.

On the other hand, the ROP can be optimized as well by using either CCA of Newitt's or API methods. Using the relationships in the second phase, and finding their impact on the hole cleaning and rate of penetration, it will be possible to determine the significance of both methods.

A new validated hole cleaning model has been developed with the aid of the field data to relate between the CCA and CCI to help evaluate the effectiveness of the used drilling mud for hole cleaning and drilling rate improvement. In addition, the drilling rate can be improved further by optimizing the drilling parameters based on drilling specific energy (DSE).

4.2 Data Analysis

Monitoring and controlling CCI and CCA simultaneously empowered have effective hole cleaning and guide us to determine the potential limit of improvement in the rate of penetration.

The ratio of YP over PV has a strong direct relationship with consistency index. The consistency index or K value will increase if the ratio increases as shown in figure-70. That means it will ensure that the consistency of the drilling fluid parameters is maintained even if it is exposed to hard circumstances such as water flow (Dilution) or high temperature (degradation).

To optimize the ratio of YP over PV and PV over YP, the optimum way is to increase the yield point and decrease PV. Optimizing the ratio of YP over PV will improve K, however, optimizing PV over YP will enhance flow behavior index. That will help to adjust the shear thing and thixotropic behavior of the drilling mud in order to have perfect functioning of CCI. The ratio of PV over YP has a strong direct relationship with flow behavior index as shown in figure-71.

The only way to see the effect of these ratios is through CCI and it will tell how they influence the hole cleaning performance by increasing or decreasing CCI, see figures-72 & 73. In order to have a clear idea about the condition of hole cleaning performance using CCI, two main factors must be adjusted optimally which are K and n. Increase of K will provide hole cleaning performance and decrease in n will ensure the same as well. See the figures -74 & 75 that illustrate the effect of K and n on CCI.

New relationship between consistency and flow behavior indices with plastic viscosity were developed. The consistency index to the power of flow behavior index is approximately equivalent to the plastic viscosity of Bingham model as shown in figure-76.

The recommended model results indicate that the model can improve the performance significantly. The ROP has increased by 72 % and the DSE has been reduced by 64%. That was the motivated work of the research of thesis. The percentages and the results of recommended model based on the study of data have been shown in the figure-77 and table -9.

4.3 Results and Discussion

After developing the hole cleaning model, new correlation of rate of penetration and how the optimization of drilling mud parameters and drilling parameters was performed to achieve effective hole cleaning and optimum drilling performance. The results were very optimistic and acceptable for discussion.

4.3.1 Hole Cleaning Model

The aim of enhancing hole cleaning is to allow the drilling engineers to maximize rate of penetration (ROP) without creating hole problems in the well such as lost circulation and stuck pipe. The ROP can be increased by optimization the drilling parameters (RPM and WOB). In order to ensure hole cleaning we combined monitoring and control of CCI and CCA simultaneously. Figure 78 shows the flowchart of the sequence of steps followed to make the hole clean before we start improving the ROP and then use DSE to increase ROP. The main steps are explained below:

- Enhance the CCI to be 5.
- Evaluate CCA to check if there is a chance of optimization of ROP performance by calculating the CCA with current measured ROP.
- If CCA is less than 0.05 it means there is chance to improve the ROP, we calculate the targeted ROP by using CCA equation.
- After that, the drilling parameters must be increased by selecting values of drilling parameters of highest ROP in the field to increase the rate of penetration by using DSE.

Using CCI alone gives only an idea about how the hole section is cleaned, but, does not tell about drilling rate performance. On the other hand, CCA has a limit of the maximum drilling rate that can be reached without causing any hole problems or cuttings accumulation. The maximum limit of CCA is 0.05. However, CCI was modified from the recommended value by Robinson which was 1.

Otherwise, the effective result of CCI will never be met in some cases, but the modification of CCI will help to have a better chance of hole cleaning. After several tests the optimum value of CCI has been found to be 5. In the model the minimum fixed value is 5. This means any value of CCI greater than 5 will ensure effective hole cleaning in the hole section and that has been noticed practically in the rig on the shale shakers.

If the value of CCI is less than 5, the CCI will not ensure effective hole cleaning since that value is below the required limit of effectiveness. Therefore, the ratio of YP over PV must be optimized

The model was applied in different fields for 4 vertical hole sections that were having the interval lengths 2000 feet, 1200 feet, 400 feet and 1800 feet respectively and one horizontal section of 3000 feet interval length. The results were optimum and the impact of hole cleaning on rate of penetration has been seen clearly and achieved optimally.

The results show that the ROP increased significantly in the hole section of the trial well in which the hole cleaning model was applied compared to the hole section of the offset well in which the model was not applied. The model has been validated in three 8 ½'' vertical hole sections in three different fields with WBM (Nacl & Kcl) and the ROP has been improved significantly 58 %, 62 % and 68 % respectively. The DSE has been decreased sufficiently to 61 %, 52 % and 58 % respectively as well. While in vertical 22'' hole section with spud mud the ROP has been increased 50 % and the DSE has been dropped optimally to 53 % as well. Finally, in 6.125'' horizontal hole section with OBM the ROP has been optimized to 44% while the DSE has been decreased to 48 %. The results are shown in table- 10 and 11. On the other hand, the graphs of the Depth VS the ROP and Depth VS DSE of the offset and trial wells can be seen in figure-79, 80, 81, 82, 83, 84, 85, 86, 87 and 88.

The torque and standpipe pressure graphs of horizontal section of trial well have been provided to show how the hole cleaning was effective in horizontal section and how hole cleaning contributed to reduce the torque 36 % and standpipe pressure 27 % which are major indicators that the hole was cleaned efficiently, see figures-89 & 90.

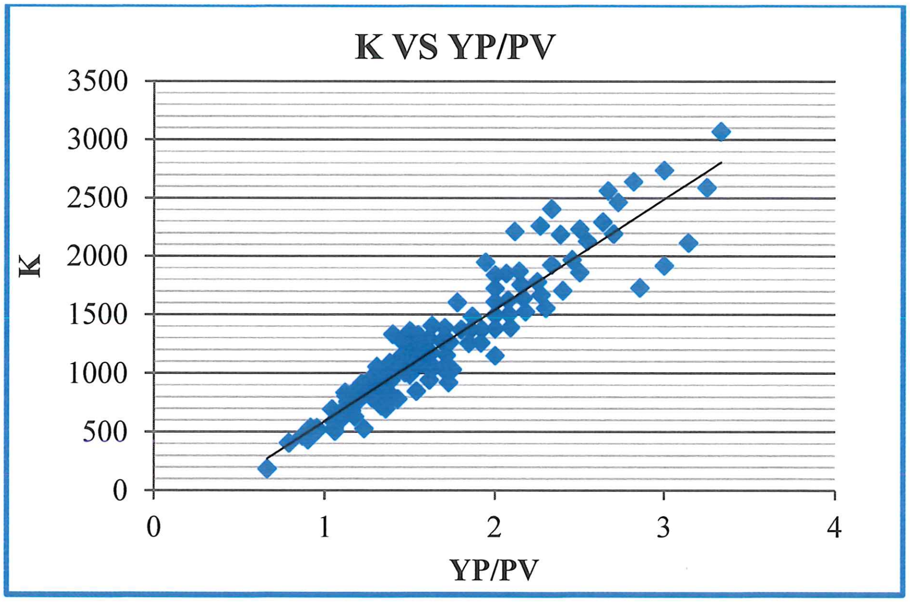

Figure 70 Relationship of Consistency Index and Ratio Of YP Over PV

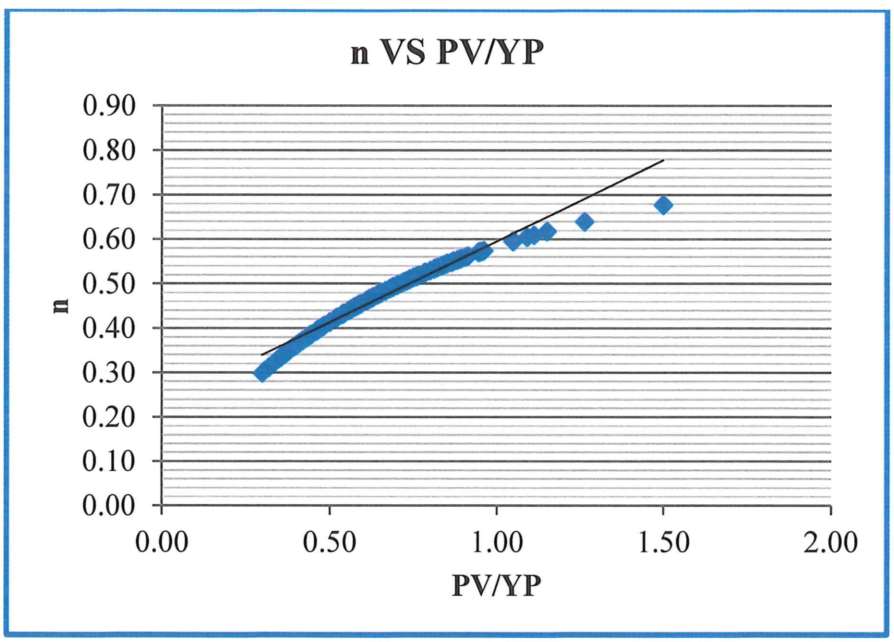

Figure 71 Relationship of Flow Behavior Index and The Ratio of PV Over YP

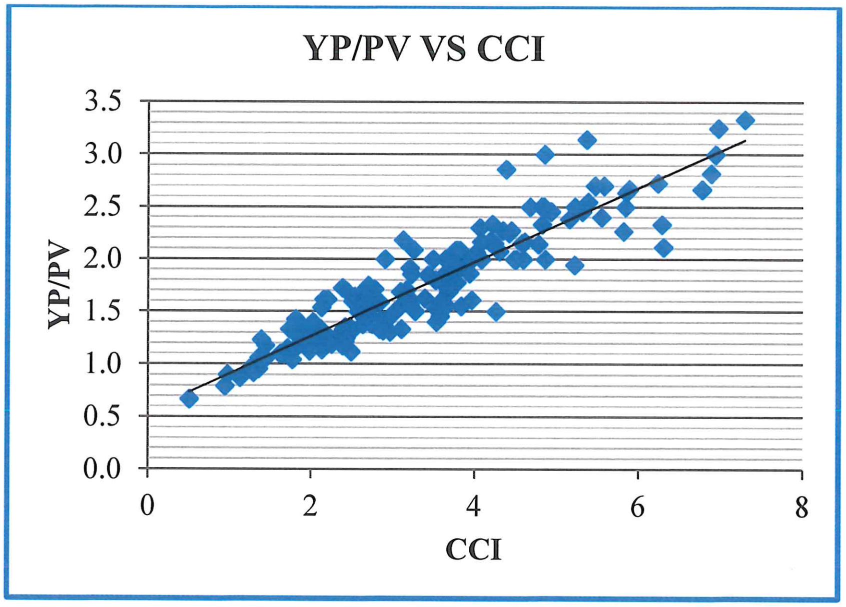

Figure 72 Effect of YP/PV Ratio on Carrying Capacity Index.

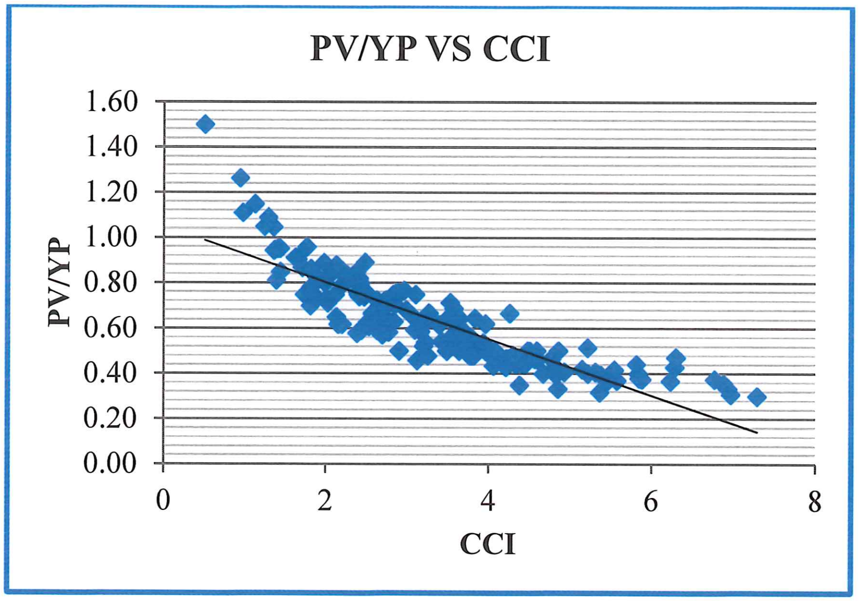

Figure 73 Effect of PV/YP Ratio on Carrying Capacity Index.

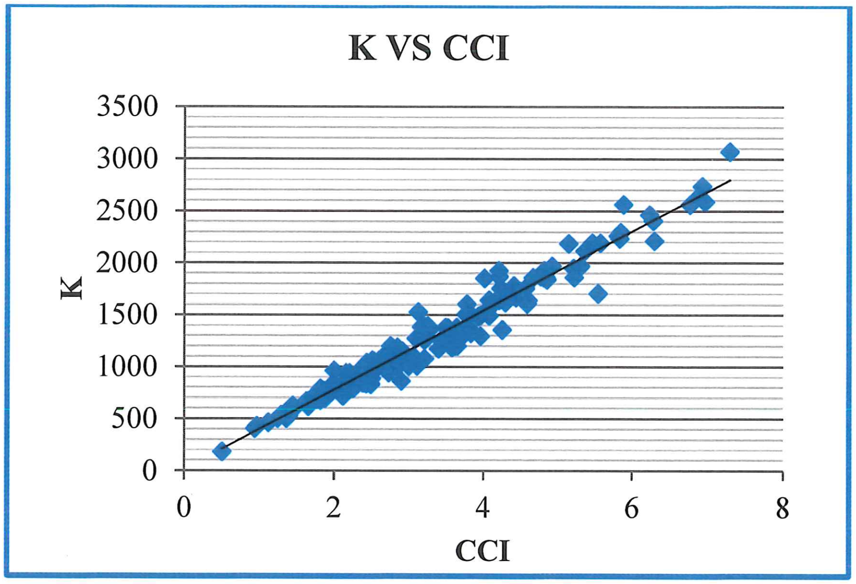

Figure 74 Effect of Consistency Index on Carrying Capacity Index.

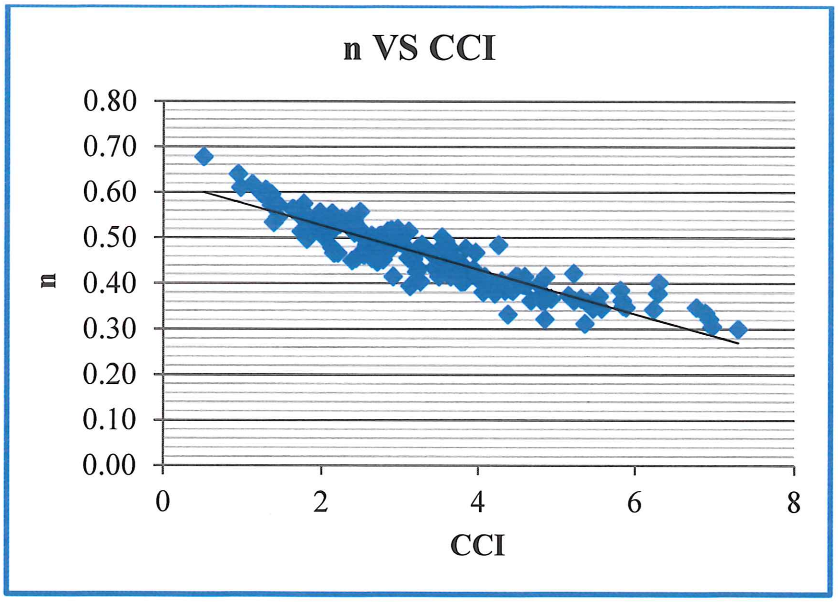

Figure 75 Effect of Flow Behavior Index on Carrying Capacity Index.

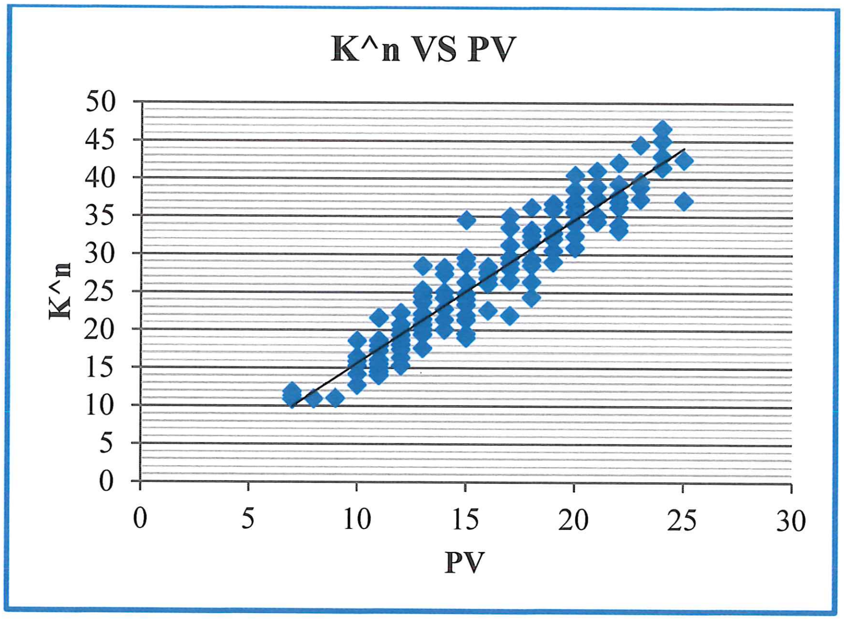

Figure 76 Relationship of K & n with Plastic Viscosity.

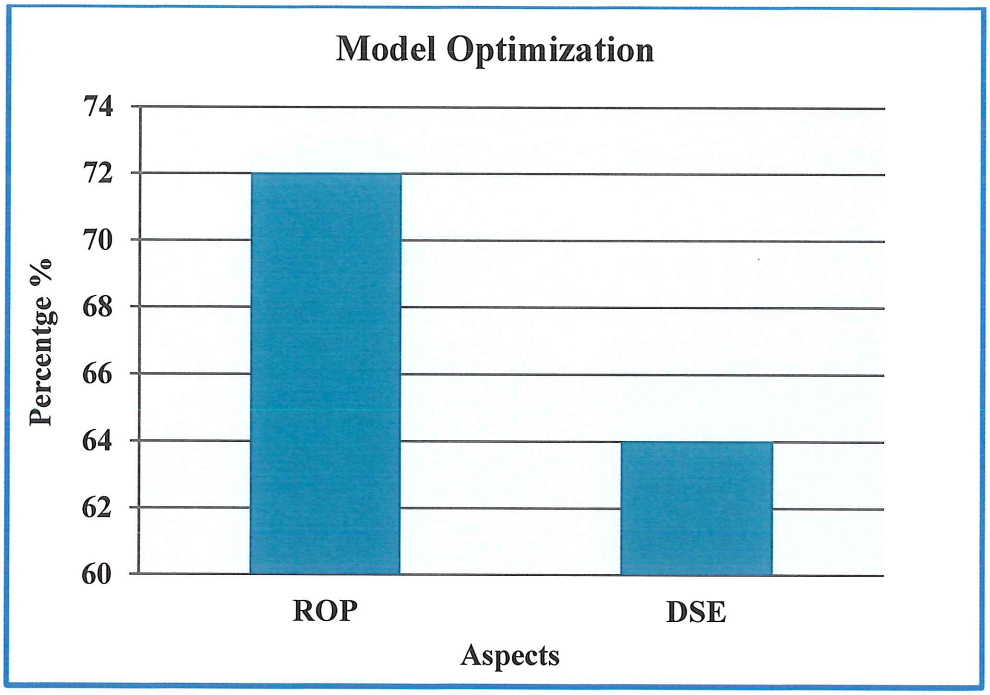

Figure 77 Model Optimization Percentages based on Study.

Model Optimization prospect	Success	Percentage %
ROP	**Improvement**	**72**
DSE	**Minimizing**	**64**

Table 9 The Recommended Hole Cleaning Model Results.

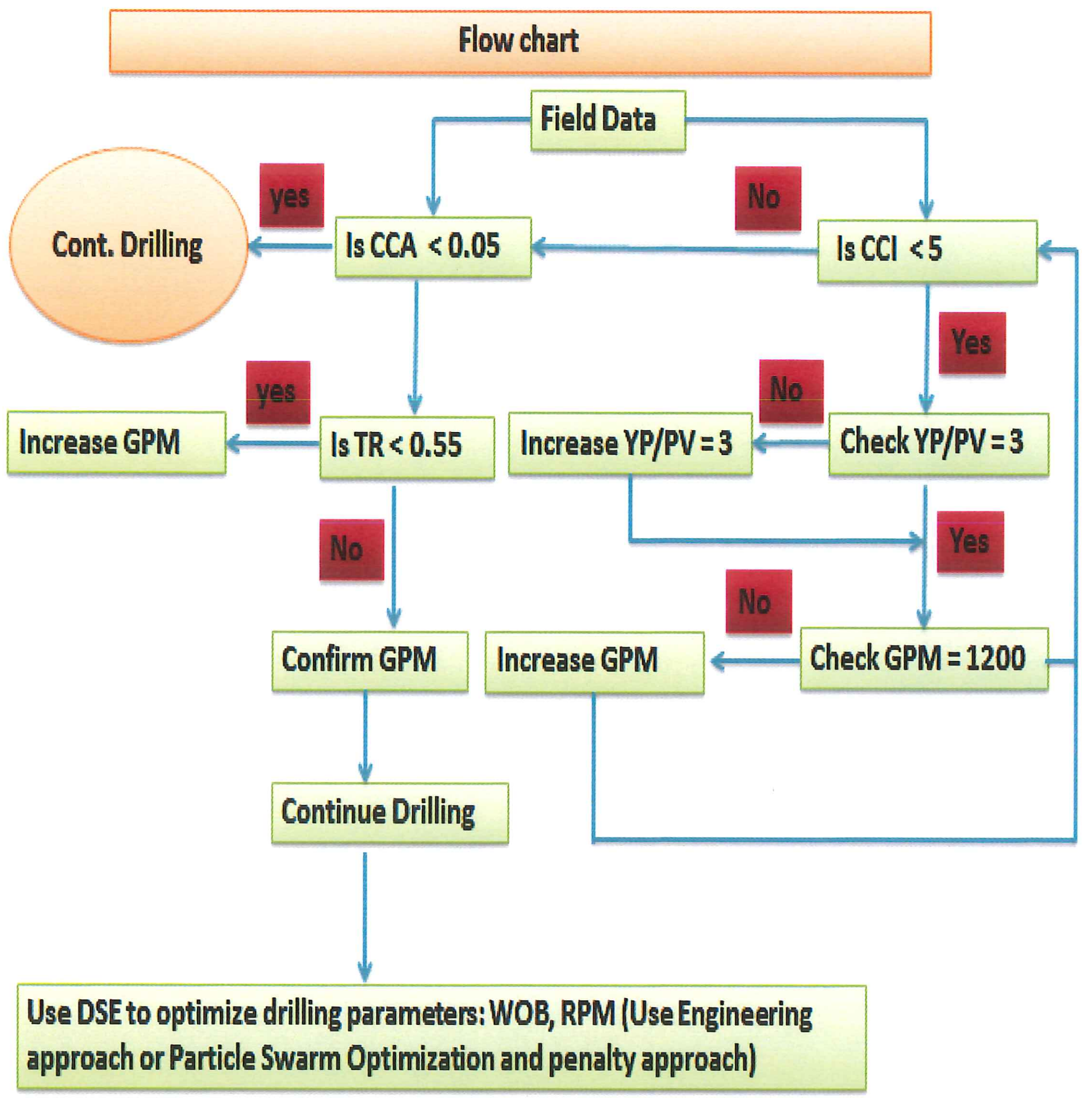

Figure 78 Flow Chart of the Model of Hole Cleaning and Drilling Rate Performance

Well	Hole Section	Mud system	Footage (ft.)	Max. ROP (ft/hr)	Avg. ROP (ft/hr)	Improvement %	Max. DSE (psi)	Minimizing %	Remark
Z1	8 1/2"	WBM-NACL	2000	70	39	58	789465	61	Offset Well
Z2				177	93		306134		Trail Well
S1	8 1/2"	WBM-KCL	1200	85	36	62	311035	52	Offset Well
S2				250	95		150800		Trail Well
M1	8 1/2"	WBM-NACL	400	81	23	66	414474	58	Offset Well
M2				185	72		174702		Trail Well
B1	6 1/8"	OBM	3000	90	56	44	795551	48	Offset Well
B2				300	100		414995		Trail Well
M3	22"	SPUD	1800	175	49	50	293131	53	Offset Well
M4				235	97		138628		Trail Well

Table 10 Results of Real Cases for Validating the Model.

Model Optimization prospect	Success	Percentage %
ROP	**Improvement**	**55**
DSE	**Minimizing**	**54**

Table 11 Results of Real Cases for Validating the Hole Cleaning Model Results.

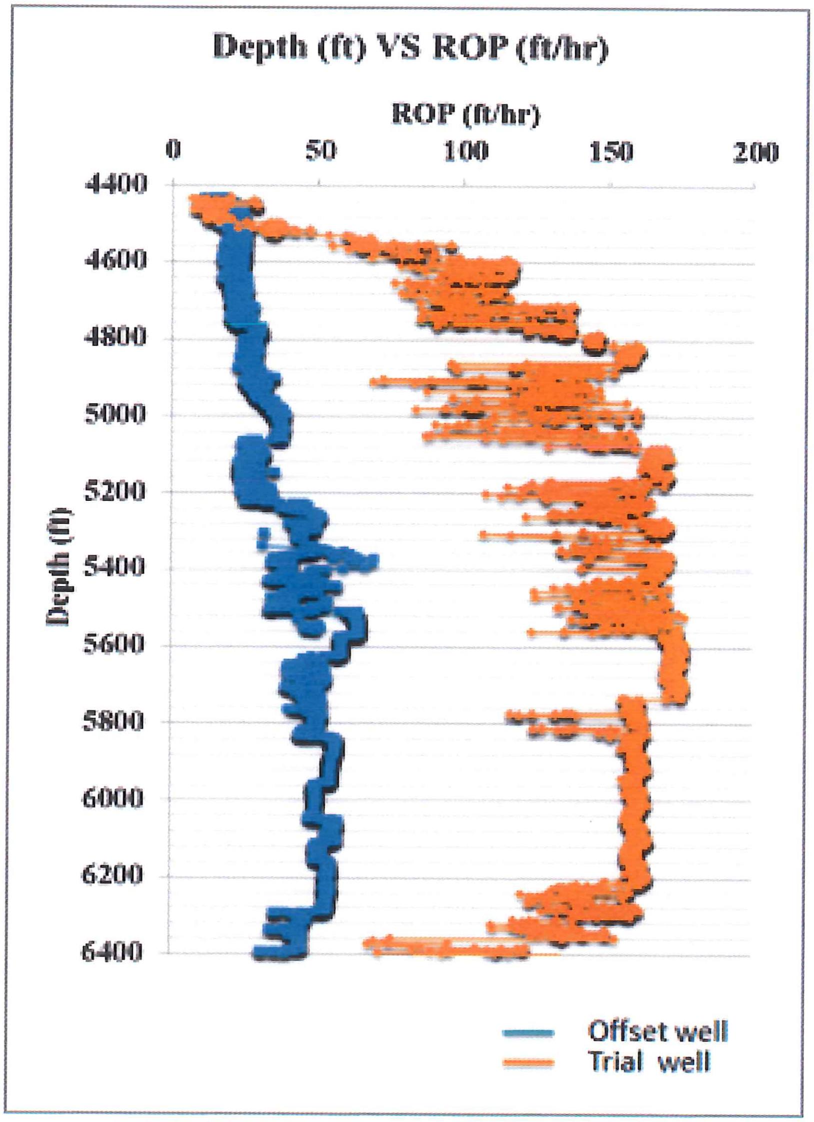

Figure 79 Depth VS ROP in 8.5'' Hole Section Z-Filed.

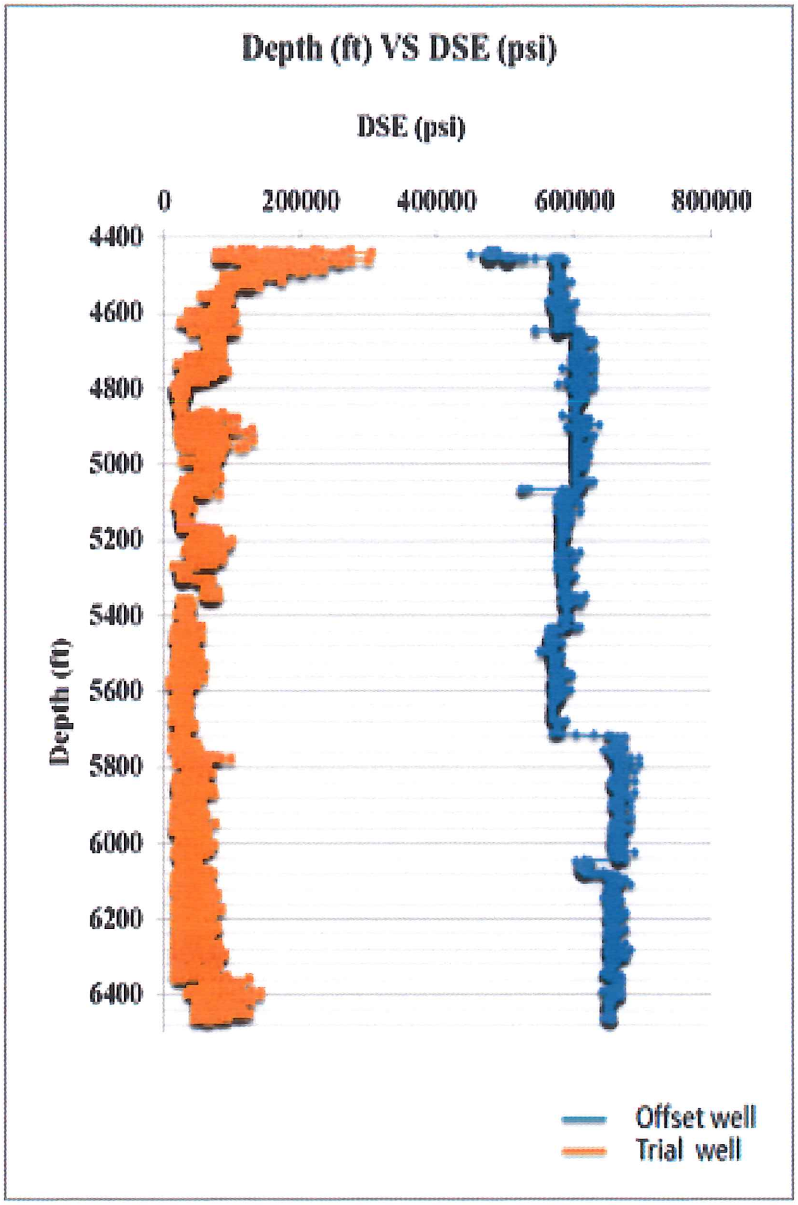

Figure 80 Depth Vs DSE in 8.5'' Hole Section Z-Filed.

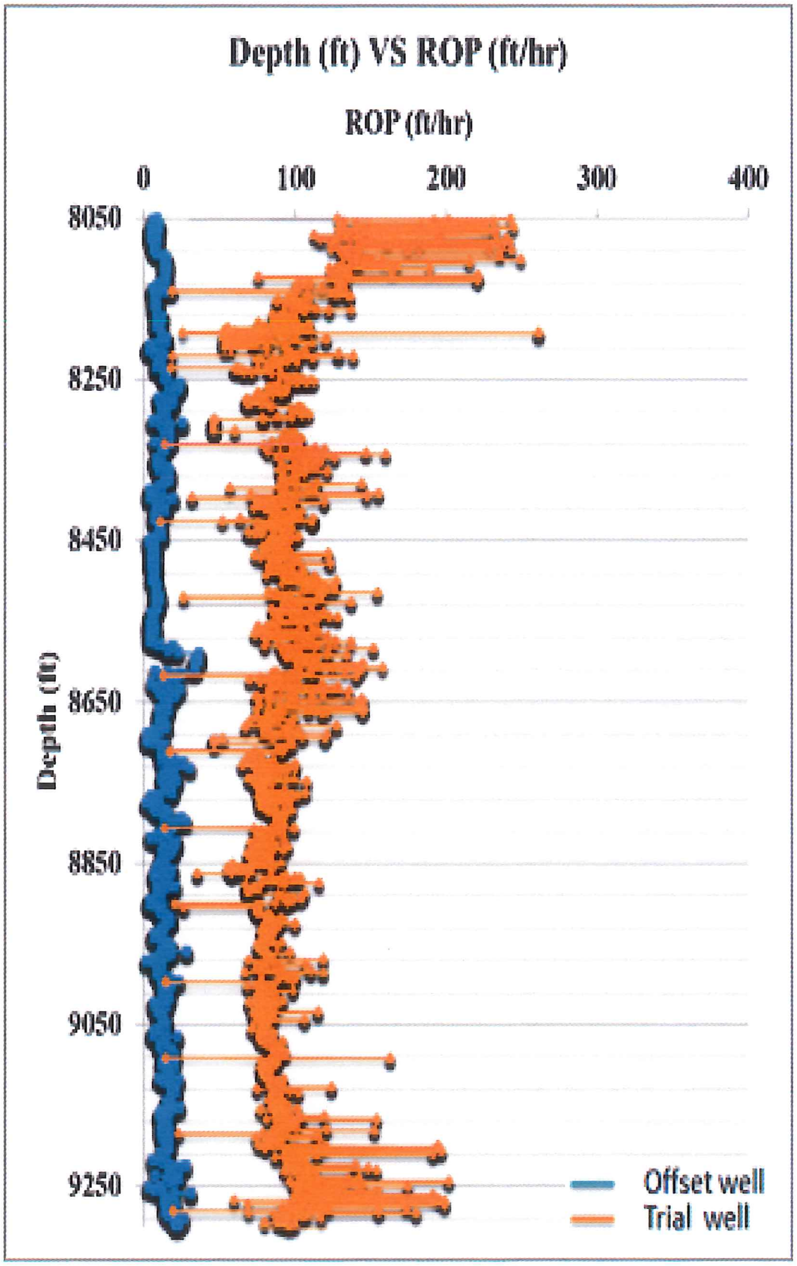

Figure 81 Depth VS ROP in 8.5'' Hole Section S-Filed.

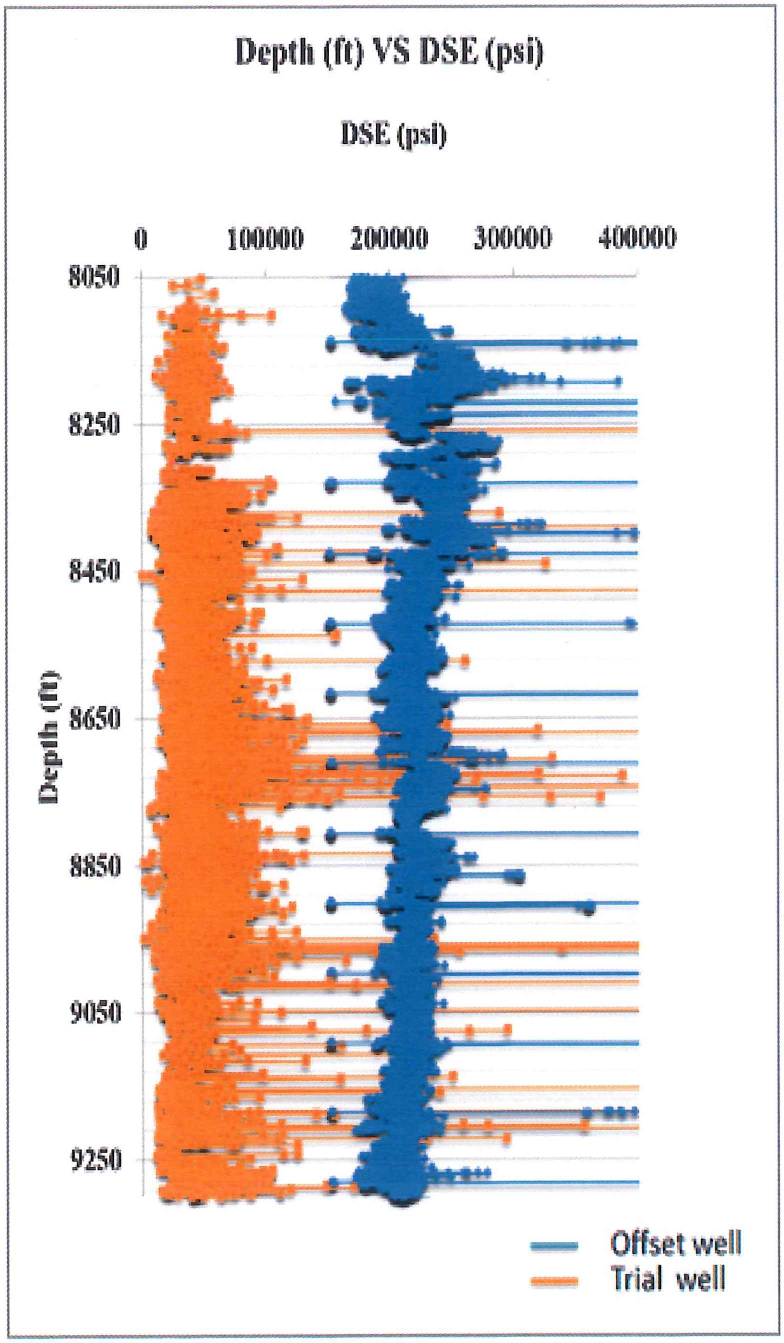

Figure 82 Depth VS DSE in 8.5'' Hole Section S-Filed.

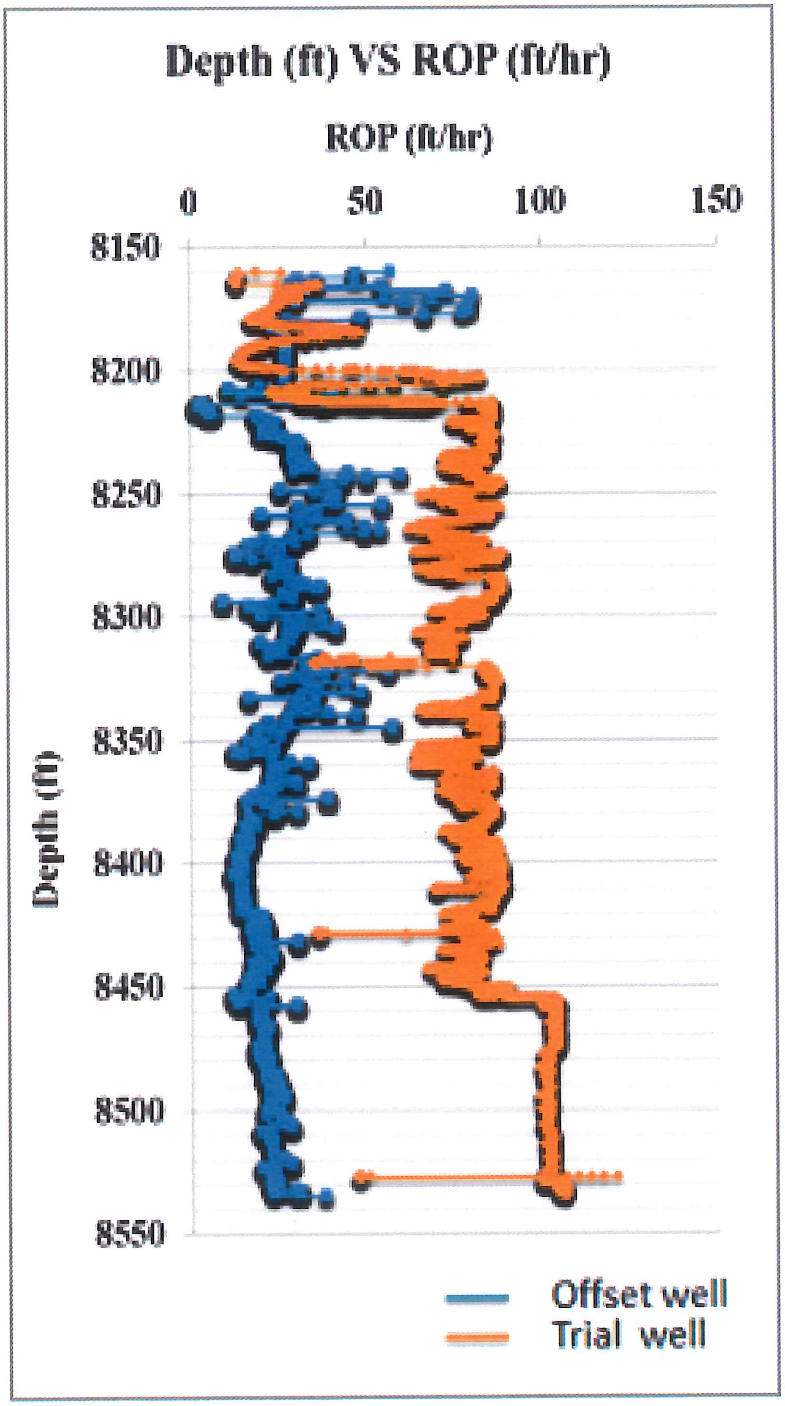

Figure 83 Depth VS ROP in 8.5'' Hole Section M-Filed.

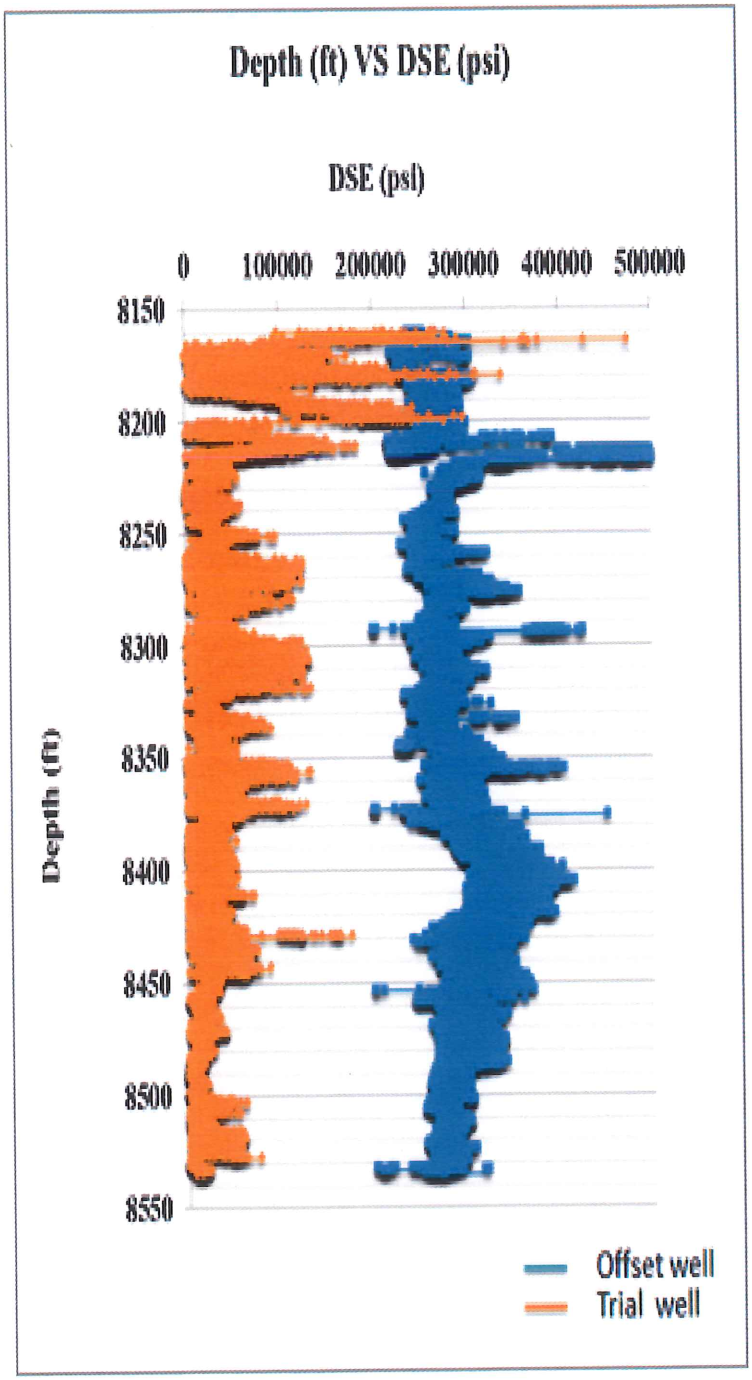

Figure 84 Depth VS DSE In 8.5'' Hole Section M-Filed.

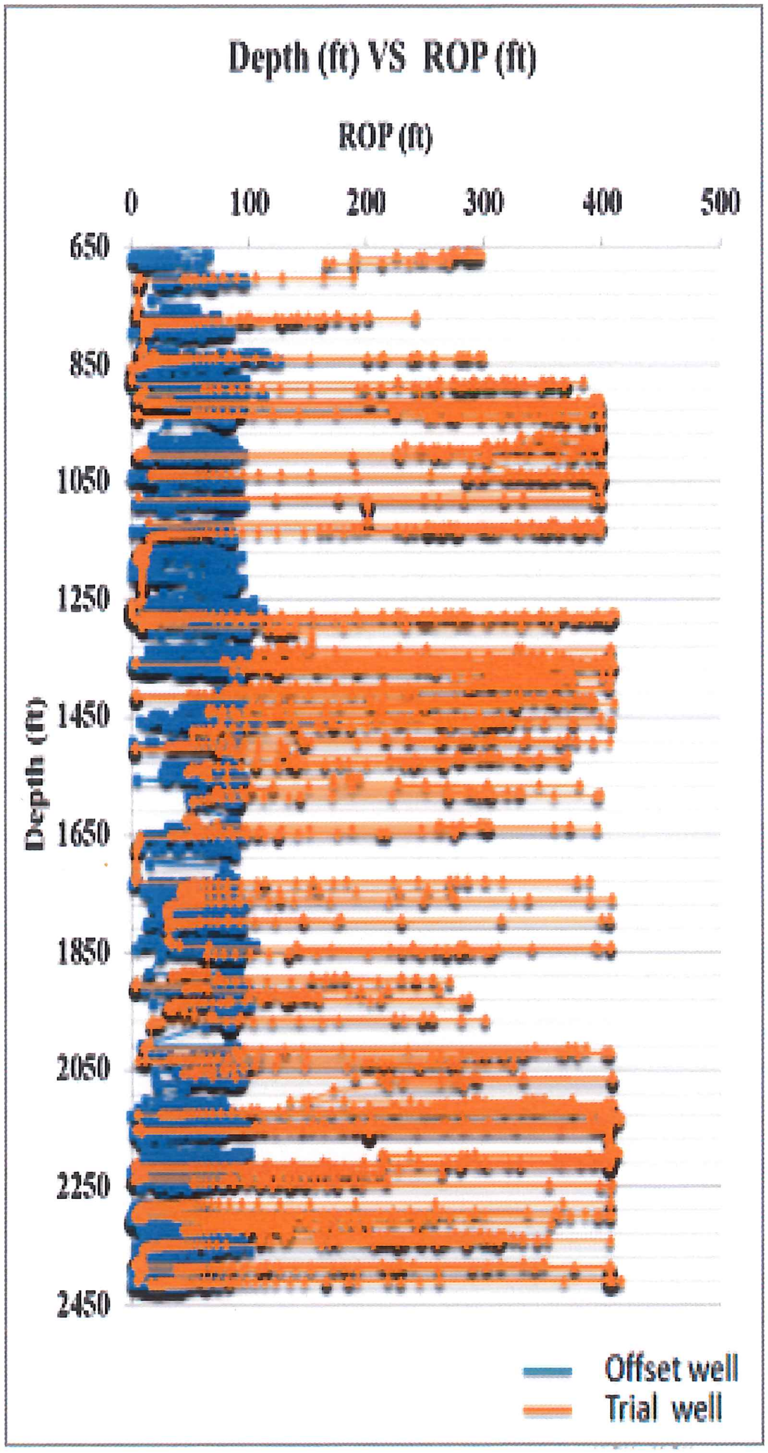

Figure 85 Depth Vs ROP in 22'' Hole Section M-Filed.

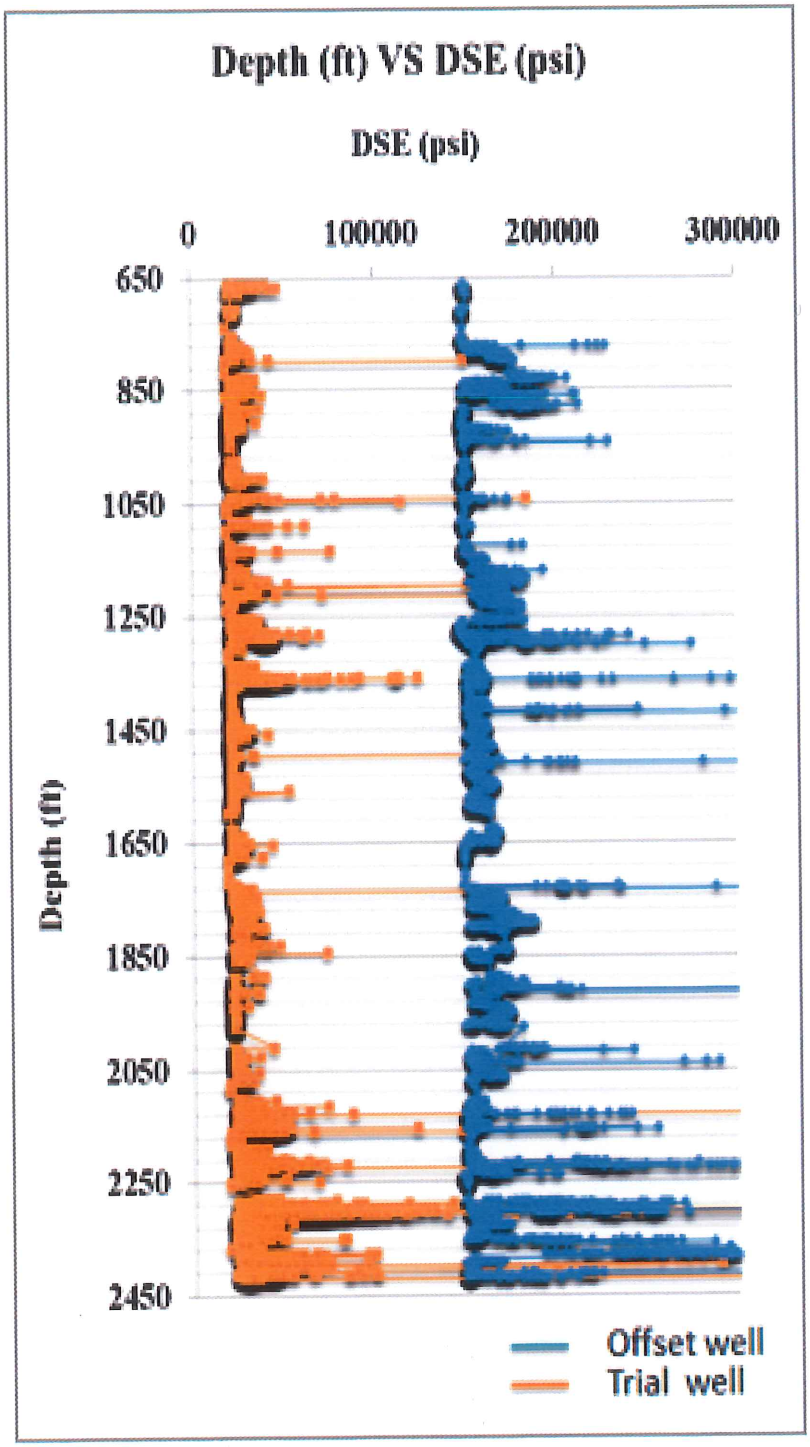

Figure 86 Depth VS DSE in 22'' Hole Section M-Field.

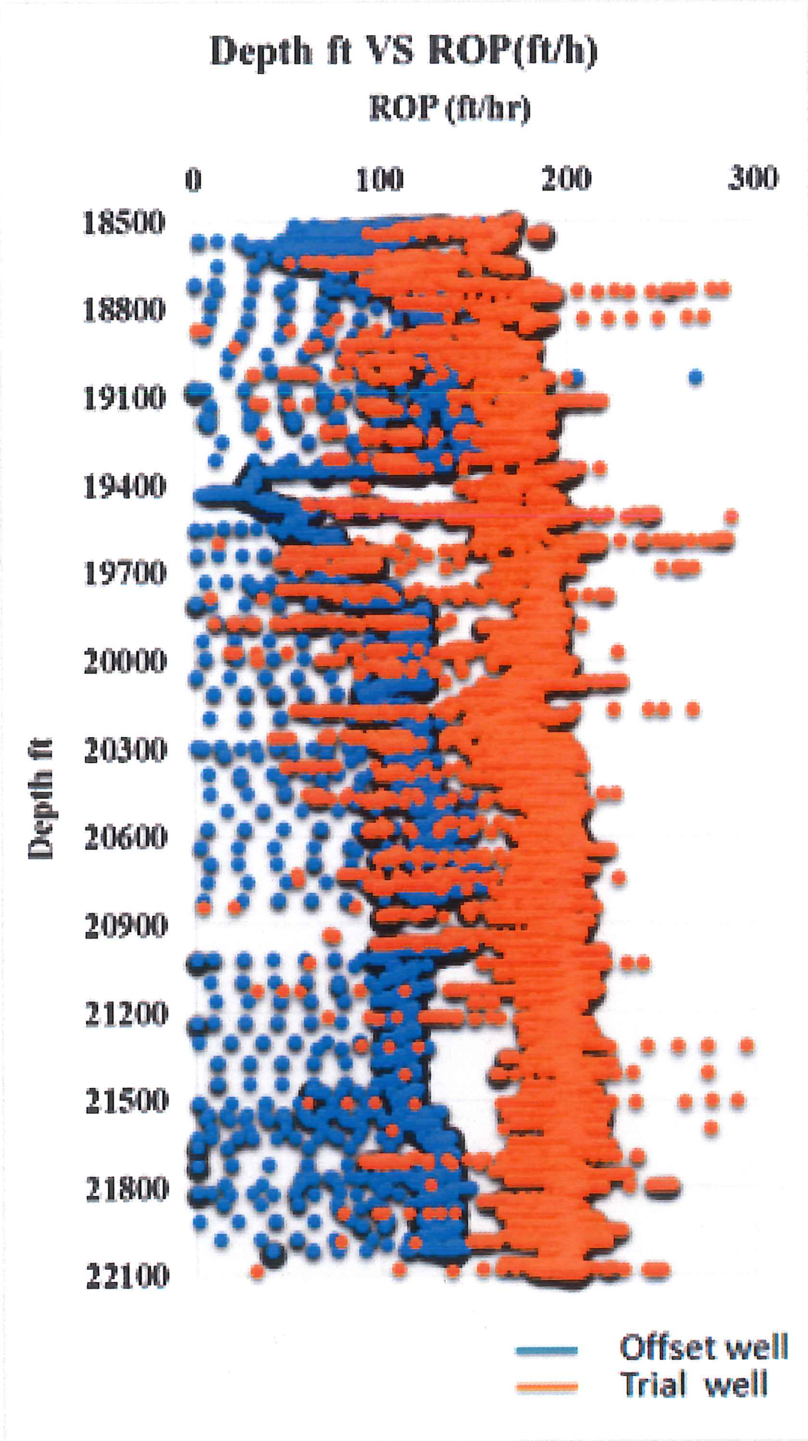

Figure 87 Depth Vs ROP in 6 1/8'' Hole Section B-Field.

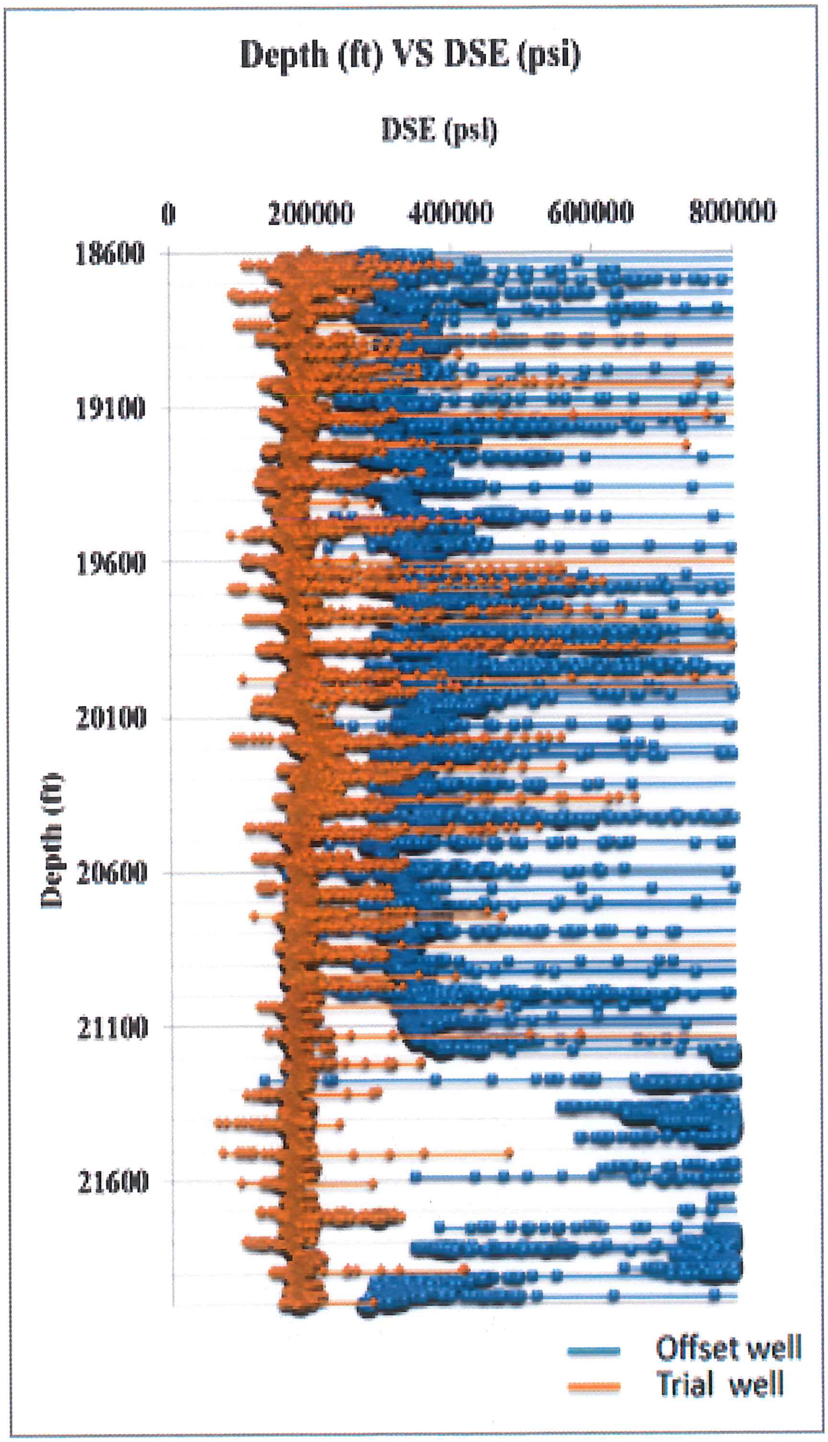

Figure 88 Depth VS DSE in 6 1/8'' Hole Section B-Field.

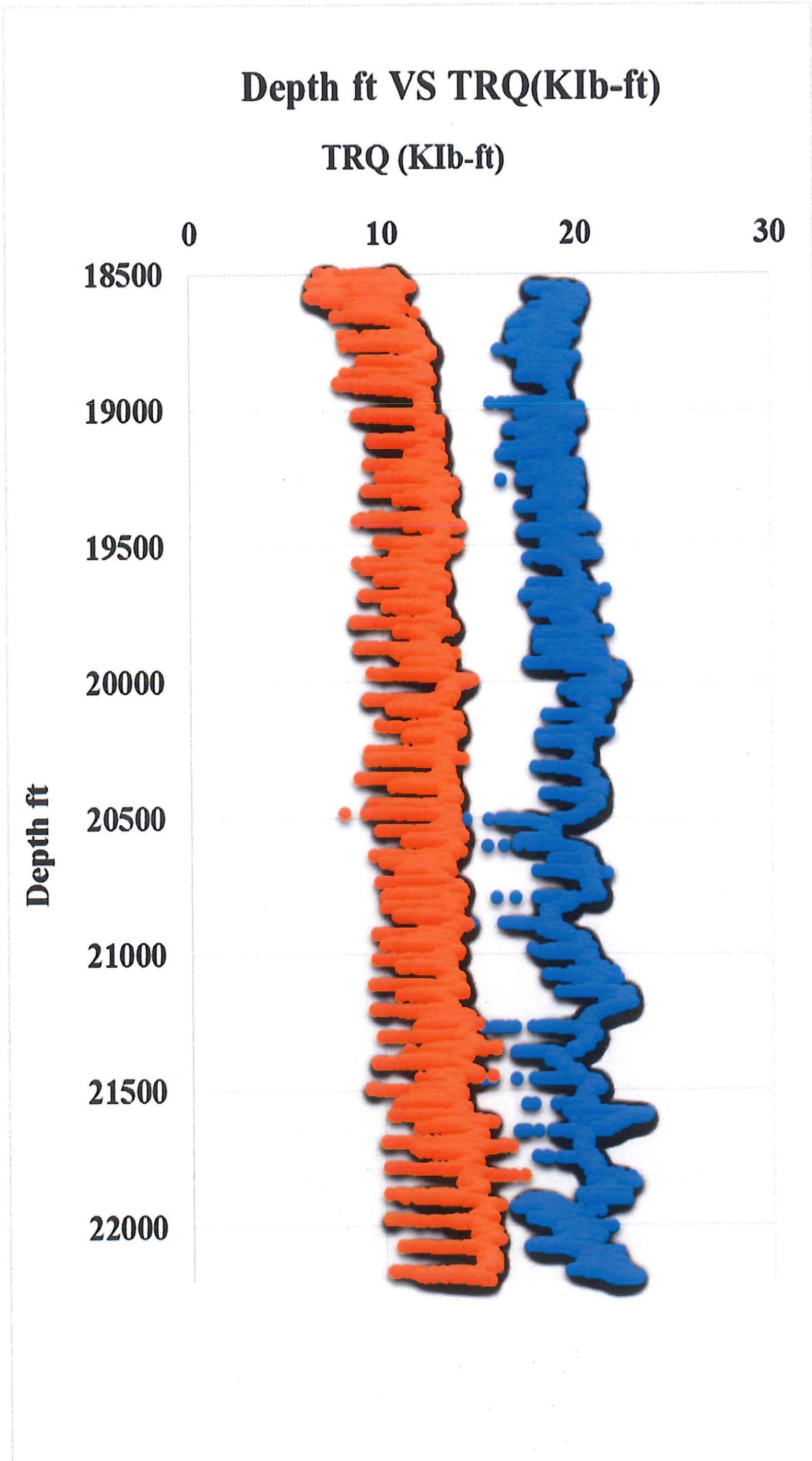

Figure 89 Depth VS Torque in 6 1/8'' Hole Section B-Field

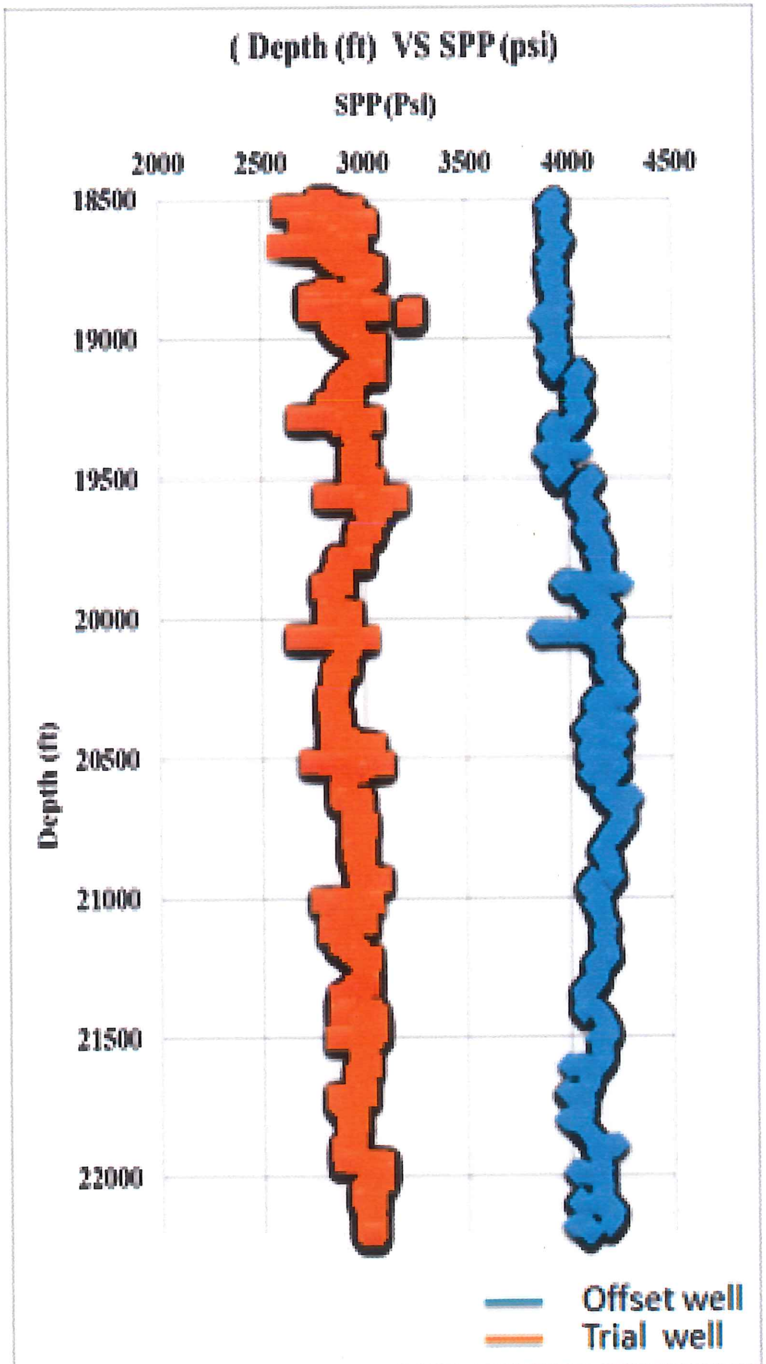

Figure 90 Depth VS Torque in 6 1/8'' Hole Section B-Field.

4.3.2 Developed Rate of Penetration Correlation

In this section the approach of Khamis was followed. To find new model of rate of penetration, it very important to obtain strong relationship amongst the input parameters and the objective output parameters of main function. It can express the relationship of correlation between the input and output parameters. Therefore, some methods were used to attain this objective. Some statistical terminologies have been defined to recognize their importance.

Correlation is a statistical method that can show the relationship of couple of variables.

Covariance is a measure of variability of two variables together. If one variable has higher values that match the higher values of the other variable and the same match can be done with small values. That means the variables have same behavior, the covariance is positive.

Variance is a measure of how far a collection of numbers is extent out.

Correlation Coefficient between two series, say x and y, equals

$$\text{correlation Coefficient} = \frac{Covariance\ (x,y)}{(Variance\ (x))^2\ (Variance\ (y))^2} \qquad (16)$$

Where,

Covariance(*x*, *y*) is the sample covariance between *x* and *y*.

$$\text{Covariance}(x, y) = \frac{1}{n-1}\ \Sigma i = n(xi - x)(yi - y) \qquad (17)$$

Variance(*x*) is the sample variance of x:

$$\text{Variance}(x) = \frac{1}{n-1}\ x\ \Sigma \mathrm{i} = \mathrm{n}\ (\mathrm{xi} - \mathrm{x})^2 \qquad (18)$$

Variance(*y*) is the sample variance of y:

$$\text{Variance(y)} = \frac{1}{\text{n}-1}\, x\, \Sigma\text{i} = \text{n (yi} - \text{y})^2 \qquad (19)$$

Nonlinear regression technique was used to develop ROP correlation.

Optimizing the drilling parameters in order to achieve high levels of (ROP) is imperative and is one objective of the research work. The established correlation is used for minimizing the DSE. This correlation contains the drilling parameters that will be boosted (WOB, RPM, HHP of bit). The optimization was attained by lessening the DSE. The DSE equation also leads to enhance the ROP by selecting better drilling parameters (WOB, RPM, T, and HHP of bit). Because of that, it is essential to develop a correlation to correlate the ROP with the drilling parameters.

The ROP is a function of several drilling parameters some of which are manageable by the drilling engineers (controllable), while others are a fact that must be accepted and dealt with (uncontrollable). In this research only controllable parameters will be treated to develop the ROP correlation.

ROP is a reaction to WOB, RPM, Torque and flow rate (Q). ROP model also can be characterized as $ROP = f1 + f2 + f3 + f4$.

Where the functions f1, f2, f3, f4, for typical and complete set of data, are

$$f1 = C1(WOB)^{C2} + C3 \qquad (20)$$

$$f2 = C4(RPM)^{C5} + C6 \qquad (21)$$

$$f3 = C7(TRQ)^{C8} + C9 \qquad (22)$$

$$f4 = C10(Q)^{C11} + C12 \qquad (23)$$

$$ROP = C1(WOB)^{C2} + C3(RPM)^{C4} + C5(TRQ)^{C6} + C7(Q)^{C8} + C9 \qquad (24)$$

The coefficients C_3, C_6, C_9 and C_{12} of the equations can be lumped into one coefficient, C_9. The coefficients (C_1, C_2, C_3, C_4, C_5, C_6, C_7 and C_8) were estimated using non-linear regression. In order to estimate the coefficients C_1 to C_8, nonlinear regression Matlab codes were developed. The results of the ROP correlation developed shows good agreement between the actual and the calculated ROP. Results obtained for the ROP correlating for offset well that was not followed the hole cleaning model and trial well that was followed the hole cleaning model has shown good estimation of the ROP with absolute error less than 12%. The graphs of ROP Calculated VS actual ROP from data and ROP Calculated VS actual ROP as a function of depth of offset and trial well can be seen in figures-91, 92, 93 and 94.

- **Methodology**

QA/QC of the Data

- Remove Null values
- Remove Negative values
- Remove outliers
- Check with physical trend
- Considered different formations and their ROP trend for removing the outliers.

Analyze the data

- Calculate statistical parameters
- Calculate correlation coefficient of each parameter with ROP
- Apply nonlinear regression to generate coefficients for the ROP correlation for selected wells.
- Calculate R-squared, Root mean square error and average absolute percentage error to estimate the fitness of curve.
- Plot Cross plot of ROP Calculated VS actual ROP from the data.
- Plot ROP Calculated VS actual ROP as a function of depth

Results of Offset Well

	ROP (ft/h)	Torque (kft.lbf)	RPM (rpm)	WOB (klbf)	Mud flow (gal/min)
Minimum	10.51	3.42	46	1.00	245.76
Maximum	57.34	9.16	120	30.04	559.96
Range	46.83	5.75	74	29.04	314.20
Average	38.22	7.21	93.44	12.39	511.98
SD	11.19	0.47	6.66	5.84	68.76

Table 12 Drilling Parameters Statistics for Offset Well

$ROP = C1\ (Torque)^{C2}\ (RPM)^{C3}\ (WOB)^{C4}\ (Q)^{C5}$ (25)

$ROP = 0.00002329\ (Torque)^{0.31036}\ (RPM)^{0.55799}\ (WOB)^{-0.079497}\ (Q)^{1.8215}$ (26)

R-squared = 0.813

Average absolute percentage error = 11.27%

Root mean square error = 4.86

Results of Trial Well

	ROP (ft/h)	Mud flow (gal/min)	RPM (rpm)	Torque (kft.lbf)	WOB (klbf)
Minimum	6.7	596	87	1.78	3.8
Maximum	176.6	709	149	14.50	29.3
Range	169.9	113	62	12.72	25.5
Average	129.19	667.10	135.06	7.08	17.22
SD	44.21	32.69	11.87	2.55	6.38

Table 13 Drilling Parameters Statistics For Trial Well.

$$ROP = C1\ (Torque)^{C2}\ (RPM/100)^{C3}\ (WOB)^{C4}\ (Q)^{C5} \quad (27)$$

$$ROP = 0.000053322\ (Torque)^{0.079138}\ (RPM/100)^{4.4581}\ (WOB)^{-0.29074}\ (Q)^{2.1451} \quad (28)$$

R-squared = 0.947

Average absolute percentage error = 10.59%

Root mean square error = 10.2

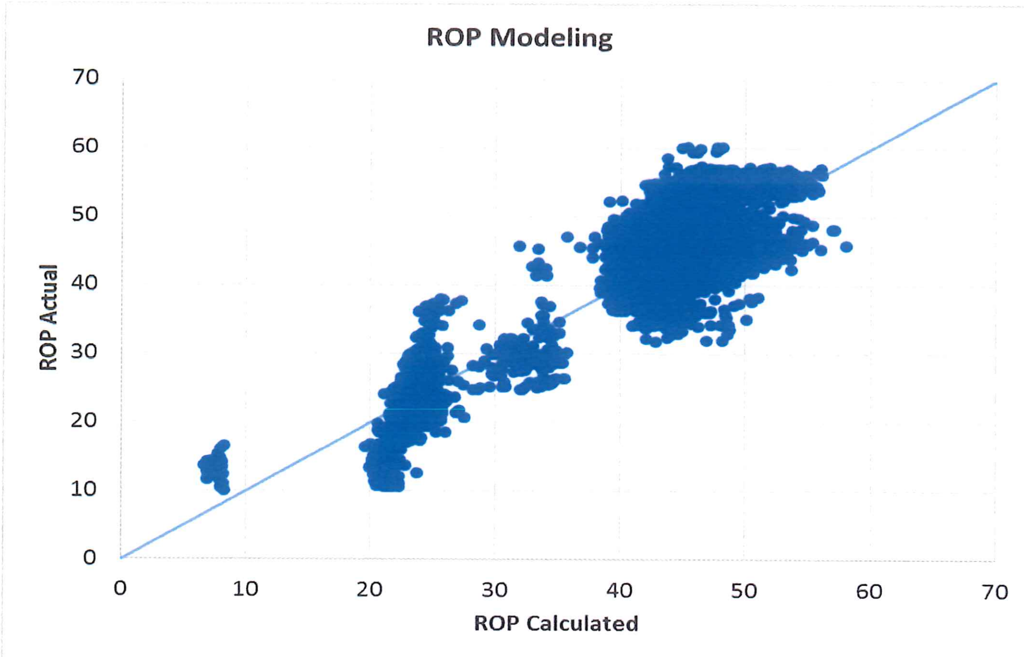

Figure 91 Measured Rop vs Calculated ROP-Cross Plot for Offset Well

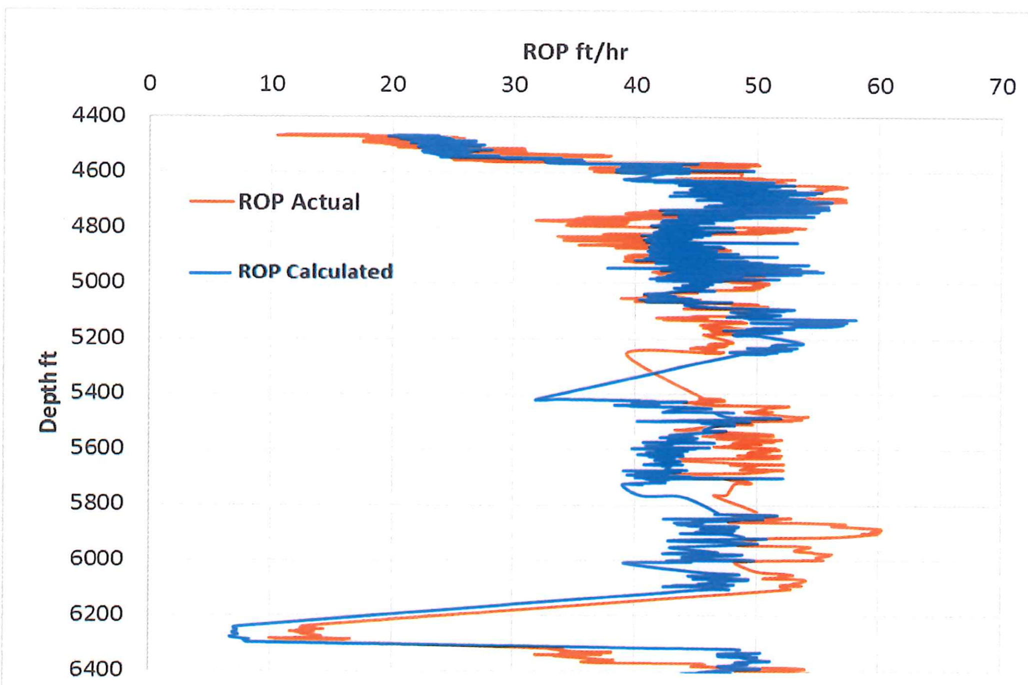

Figure 92 Calculated ROP VS Actual ROP as Function of Depth of Offset Well

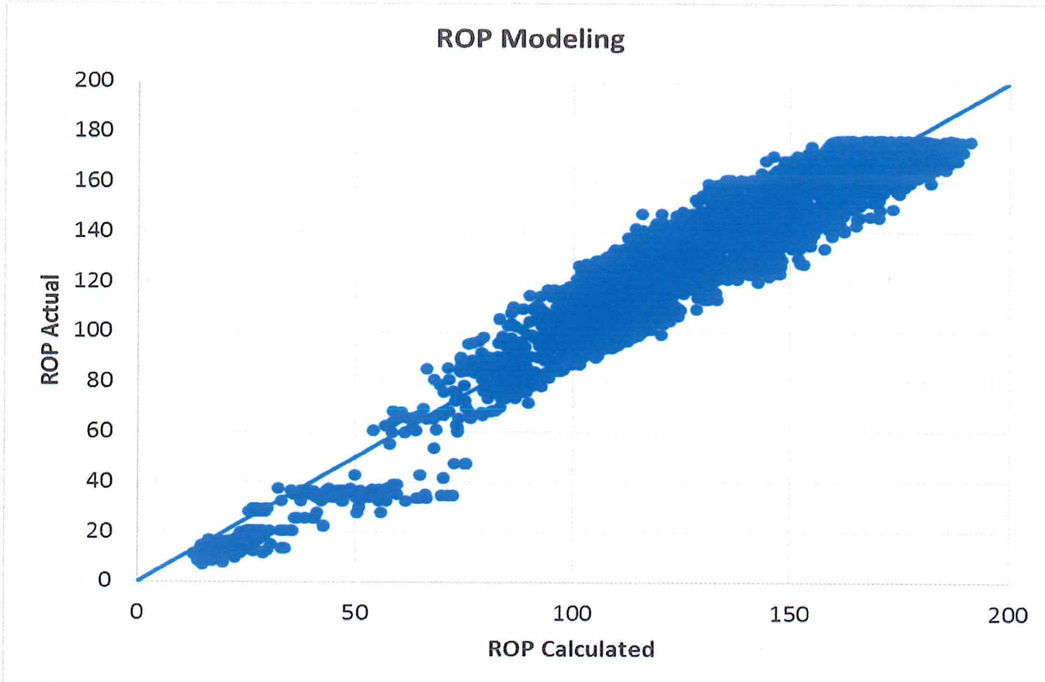

Figure 93 Measured ROP vs Calculated ROP-Cross Plot for Trial Well

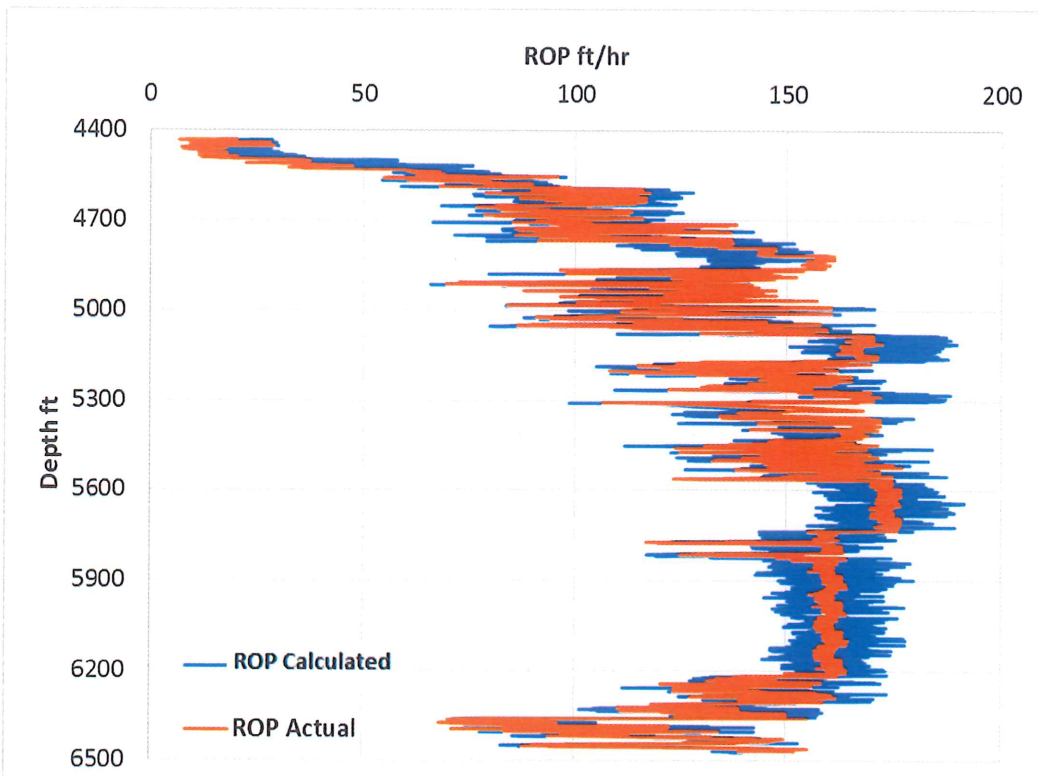

Figure 94 Calculated ROP VS Actual ROP as Function of Depth of Trial Well

4.3.3 Optimization of Hole Cleaning Parameters and Drilling Parameters

The aim of the optimization is ensure effective hole cleaning by optimizing the drilling parameters (PV and YP) and to maximize rate of penetration (ROP) by optimizing the drilling parameters (RPM and WOB).

1- **<u>First optimization method was by using CCA & CC:</u>**

- Reduce PV value among the range (10 cP – 12 cP).
- Increase YP value among the range (28 lb/100ft^2 - $30lb/100^2$).
- Enhance the CCI to be 5.
- Evaluate CCA to check if there is a chance of optimization of ROP performance by calculating the CCA with current measured ROP.
- If CCA is less than 0.05 it means there is chance to improve the ROP, we calculate the targeted ROP by using CCA equation.
- After that, the drilling parameters must be increased by selecting values of drilling parameters randomly of highest ROP in the field to increase the rate of penetration.

2- **<u>The second optimization method was by using CCI, CCA & DSE:</u>**

- Enhance the CCI to be 5.
- Calculate CCA with current measured ROP to find out if it is less than 0.05.
- If CCA is less than 0.05, calculate the targeted ROP by using CCA equation.
- If there is chance to improve the ROP to the targeted value use the DSE to determine the optimum drilling parameters as shown in figure-95. Figure-95 shows the flow chart we used to determine or select the optimum values of drilling parameters to give the minimum value of DSE. Three values for WOB & RPM were selected of the highest ROP in the field. This is a try and error method to reach the best WOB & RPM values that will attain improved ROP.
- Apply the selected drilling parameters in the DSE equation to give minimum value of DSE.

3- **The third method is proposed for optimization ROP by integrating two techniques of optimization**:

- Particle swarm optimization technique (PSO) and Penalty approach. This method is based on Khamis approach in PSO method to calculate the optimum drilling parameters, but is improved by incorporating penalty approach. Particle swarm optimization (PSO) does not make any assumption about the problem or guarantee if the problem was optimized. Therefore, it is used usually for problems that are partially irregular, noisy, or change over time. Where PSO algorithm represented according to the following equality (Shi 1998):-

$$V_{id}^{k+1} = v_{id}^{k} + c_1 r_1^{k}(pbest_{id}^{k} - x_{id}^{k}) + c_2 r_2^{k}(gbest_{d}^{k} - x_{id}^{k}) \qquad (29)$$

$$X_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \qquad (30)$$

Where,

V_{id}^{k} and x_{id}^{k} stands separately for the speed of the particle "i" at its "k" times and the "d" dimension quantity of its position.

$pbest_{id}^{k}$ represents d-dimension quantity of individual 'i" at its most optimist position at its "k" times.

$gbest_{id}^{k}$ represents the d-dimension quantity of the swarm at its most optimist position at its "k" times. In order to avoid particle being far away from the searching space, the speed of the particle created at its each direction is confined between $-vd_{max}$, and vd_{max}. If the number of vd_{max} is too big, the solution is far from the best, if the number of vd_{max} is too small, the solution will be the local optimism; c_1 and c_2 represent the speeding figure, regulating the length when flying to the most particle of the whole swarm and to the most optimist individual particle. If the figure is too small, the particle is probably far away from the target field, if the figure is too big, the particle will maybe fly to the target field suddenly or fly beyond the target field.

The proper figures for c_1 and c_2 can control the speed of the particle's flying and the solution will not be the partial optimism. Usually, c_1 is equal to c_2 and they are equal to 2. r_1 and r_2 represent random fiction, and 0-1 is a random number.

For the other technique, penalty method is used for converting a constrained optimization problem into a sequence of unconstrained problems. In penalty approach, three equations have been applied to control the data to obtain the optimum drilling parameters which are WOB & RPM of the Area of optimization.

The three equations contain Torque (TRQ), Carrying Capacity Index (CCI) and Cutting Concentration in Annulus (CCA) values. The first equation is representing penalty approach by using of torque (TRQ), maximum torque (TRQ_{max}) of used drillpipe in certain hole section and mean value of torque data (TRQ_{mean}). Penalty Approach was used to make sure not to exceed the maximum torque.

The second equation is representing penalty approach by using of Carrying Capacity Index (CCI), maximum Carrying capacity Index (CCI_{max}) and mean value of Carrying capacity index values (CCI_{mean}). The penalty approach was used to make sure the minimum selected value is 5 and above of data.

The third equation is representing Cutting Concentration in Annulus (CCA), maximum Cutting Concentration in Annulus (CCA_{max}) and the mean values of Carrying Capacity in Annulus (CCA_{mean}). The Penalty Approach was used to ensure the selected value are not exceeding 0.05 and more than 0.035.

The following equations were applied:-

$$OBJ = DSE + PENALTY \tag{31}$$

Where,

$$OBJ = DSE + P1 + P2 + P3 \tag{32}$$

PENALTIES are

1) TRQ < TRQ_{max}
2) CCI > 5
3) CCA <= 0.05

Accordingly

Where,

<u>P1 is the torque term where,</u>

$$P1 = \left(\frac{TRQ - TRQmax}{TRQmean}\right)^2, IF\ TRQ > TRQmax\ \ and\ 0\ if\ TRQ <= TRQmax.$$

<u>P2 is the CC1 term where,</u>

$$P2 = \left(\frac{\text{CCI}-\text{CCImax}}{\text{CCImean}}\right)^2, \quad IF\ CCI < CCImin\ and\ 0\ if\ CCI > 5.$$

<u>P3 is the CCA term where,</u>

$$P3 = \left(\frac{CCA-CCAmax}{\text{CCAmean}}\right)^2, \quad IF\ CCA > CCAmax\ and\ 0\ if\ CCI <= 0.05.$$

- Matlab codes were developed to obtain the improvement. Three codes were established to the main code, the PSO code and the DSE function code (include the Penalty approach). Based on the calculation, the optimum parameters that reduce the DSE were determined.

- The flow chart in Figure-96 shows the optimization procedure followed in this study. In the main code the data will be read, tested for quality and examined. The constants and weights will be set and the lower and upper limits for the parameters would be set also. Through the PSO code the drilling parameters will be assigned and then the objective function will be called for optimization.

- Applying PSO a partly will give the maximum drilling parameters of the selected data and this is not logical. For that reason we added the application of penalty approach to shift the selection of optimum drilling parameters to the area of optimization as can be seen in the figure -97.

- The PSO approach guides the solution towards the optimum one (in the range of the maximum and minimum that were given) until the minimum value of the DSE is being achieved. Then by using the Penalty approach in the objective function code, the DSE will be optimize which will eventually drag the parameter to the optimum values.

- The required data to run the code are: hole section, WOB, ROP, RPM and torque. The optimization values for the data application on trial well and the data application on offset well are shown in Table 13 and Table 14, respectively.

- The eventual aims of optimization are (1) reducing drilling time and (2) saving money. Decreasing drilling time can be attained by maximizing the ROP through drilling with the best parameters. The combined methods results display that the best parameters are within the boundaries of the examine domain.

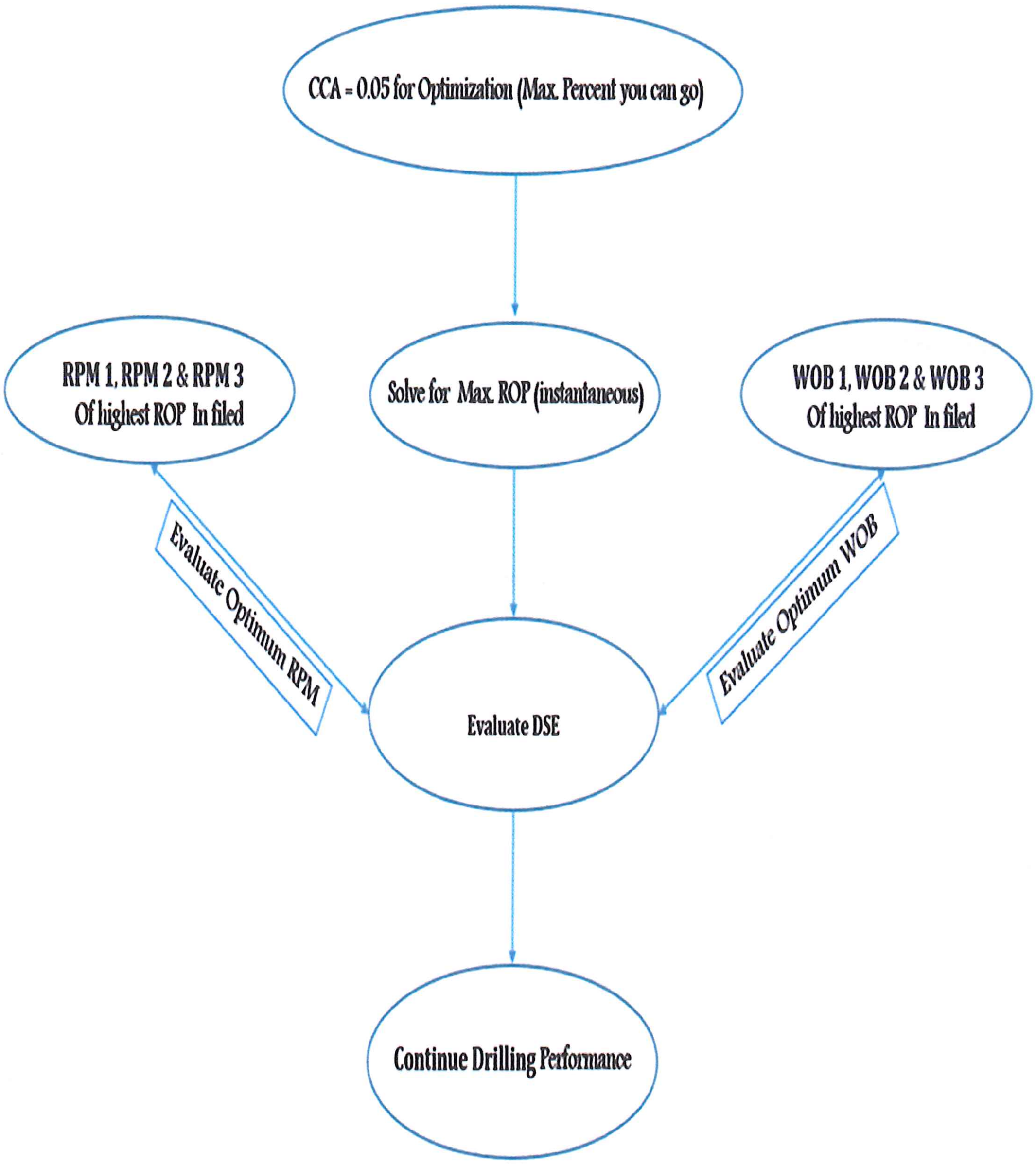

Figure 95 Flow Chart of Optimization of Drilling Parameters by Using Engineering Approach

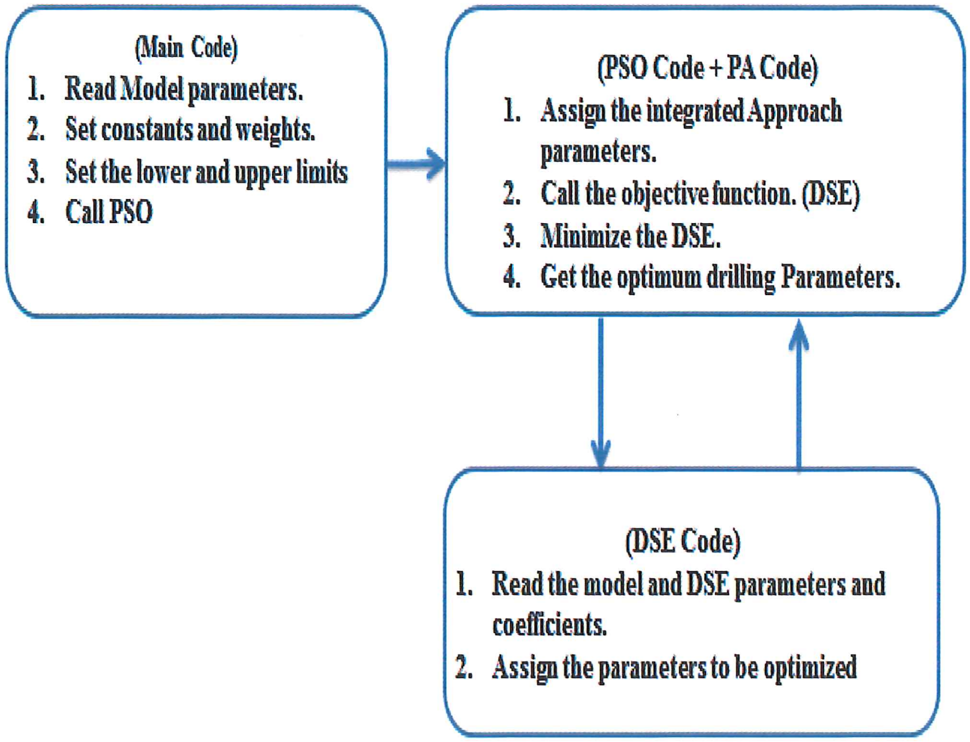

Figure 96 Flow Chart of Optimization of Drilling Parameters by Using (PSO + PA) Integrated Approach

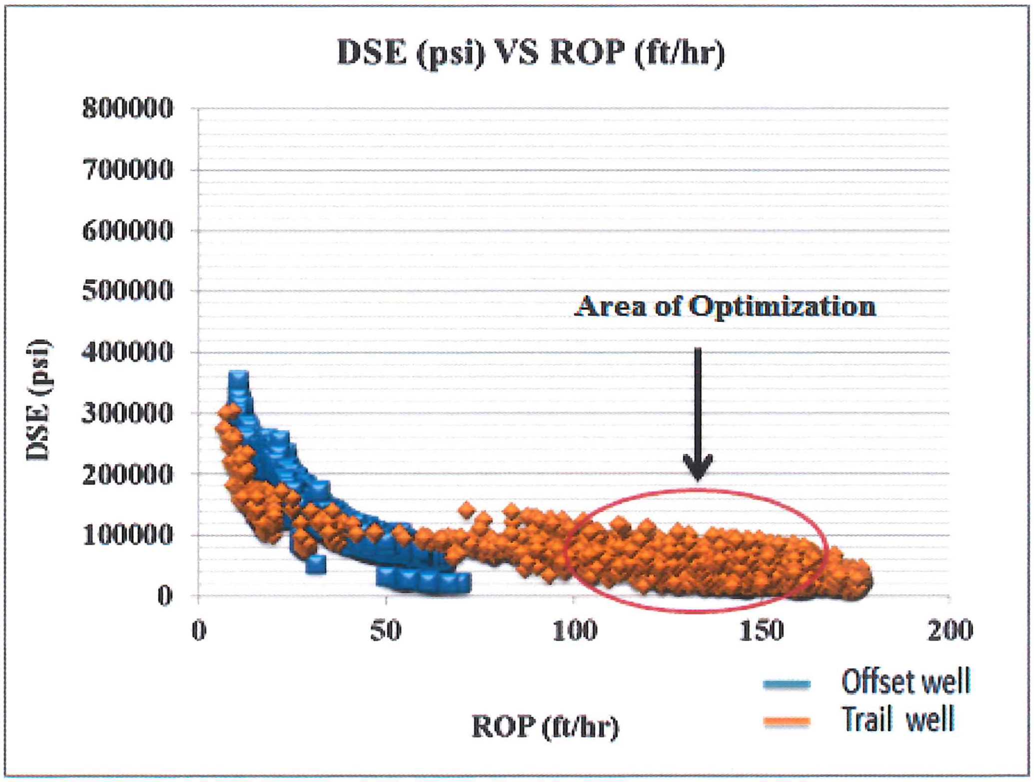

Figure 97: DSE VS ROP to Select Optimum Drilling Parameters of Matlab Coding.

Parameter	Maximum	Minimum	Optimized Valued	Optimized ROP
RPM	149	87	113	59
WOB	29	4	22	

Table 14: Optimization of Data Application Trial well

Parameter	Maximum	Minimum	Optimized Valued	Optimized ROP
RPM	120	46	77	41
WOB	30	1	22	

Table 15: Optimization of Data Application Offset well

CHAPTER 5

Conclusions & Summary

After completing this work, the hole cleaning model is an effective tool to ensure optimum drilling fluid and drilling parameters. The hole cleaning model can be applied in all challenging hole sections with different mud systems. The hole cleaning model achieves perfect hole cleaning efficiency and well drilling performance that lead to cost effectiveness and contribute to well delivery.

- Understanding the drilling fluid properties and their influence on hole cleaning and drilling rate is important to realize how to optimize the design of the mud rheology and selecting optimum values for them.

- Combining and utilizing the CCI and CCA optimally with DSE have a great impact on the effectiveness hole cleaning and drilling rate performance.

- The model is an effective tool for drilling engineer and drilling foreman to ensure the optimum mud parameters for hole clearing and maximum limit of ROP based on cuttings volume in annulus.

- The hole cleaning model increased the ROP and minimized DSE significantly; the average increase in ROP percentage is almost more than 55% in all wells, on the other hand, the average decrease in DSE is almost more than 54 % in all wells.

- The developed ROP correlation with respect of drilling parameters is more realistic than other correlations. Because the other correlations that have parameters of mud rheology are qualitative relationships only. Because if total losses has been encountered, the influence of parameters of mud rheology on hole cleaning will disappear, however, if the drilling parameters have been applied and controlled optimally, the ROP performance can be maintained.

- Optimization of drilling parameters to select the optimum values has a major impact on drilling rate by minimizing DSE.

- The real time values of the drilling fluid rheology while drilling down hole will give a better application of cuttings concentration in annulus and carrying capacity index.

- Using the Hole cleaning model in the vertical and horizontal wells on all drilling and work over rigs will extremely ensure a great impact on rate of penetration.

- The Hole cleaning model is perfect to achieve the best cost effectiveness of drilling and dilution.

- Applying the hole cleaning model will reduce the drilling time by increasing the ROP optimally and reducing flat time by ensuring effective hole cleaning of drilled section.
- The hole cleaning model can minimize pumping sweeps, wiper trips, losses of circulation zones, the running and cementing casing job as well.

- The hole cleaning model can help even if the drilling engineer decide to combine the hole sections in one long hole section as an initiative of optimization.

Recommendations

- Engineering approach of optimization of drilling performance must be used to determine the optimum drilling parameters.

- Applying the model in RTOC (Real Time operating Center) so that all monitored wells will ensure the recommended and perfect performance.

Appendix

Simple flow chart for hole cleaning determinations and decision making

Input Data

Drilling mud properties and well configurations

Calculations

Cutting concentration In Annulus (CCA) and the carrying capacity index (CCI)

Decision Making

IF CCA > 5% or CCI < 1 Then Bad Hole Cleaning

IF CCA <= 5% or CCI > 1 Then Good Hole Cleaning

The detailed calculations of hole cleaning can be summarized as following:

Input Data

The required data include:

1. Hole Size
2. Mud Type
3. Footage
4. Hours spent for drilling the footage
5. Mud Density (in PCF and PPG)
6. Funnel Viscosity
7. Plastic Viscosity (PV) in cp.
8. Yield point (YP) in $lb/100ft^2$
9. WOB (Klb), RPM (Rev per Min), Stand pipe pressure (Psi) and Torque (lb-ft).
10. Total flow area of bit. (Sq.in)
11. Initial Gel and final gel. ($lb/100ft^2$)
12. Flow rate of Mud Pump. (GPM)

Preliminary Calculations

Before using the hole cleaning models, the following parameters should be determined:

1. Rate of penetration (ROP)

2. Consistency index (K) and Fluid behavior index (n)

3. The apparent and effective viscosities

4. The annular velocity (Vann)

5. The critical velocity (V_c).

6. The cutting rise velocity (V_{cr})

7. The cutting slip velocity (Vs)

8. Consistency index to the power n that is equivalent to plastic viscosity term. K^n

9. The velocity of Nozzles.

10. The pressure drop at the drilling bit

11. The hydraulic horsepower (HHP)

12. Hydraulic Horse Power Per square inch (HSI).

13. The jet impact force (Fj)

14. Transport ratio (TR)

15. Ratio of (PV/YP), (YP/PV).

16. Drilling Specific Energy (DSE)

Model Calculations and Decision Making

Determine the cutting concentration in the annulus (Cc), using the following models:

1. **Newitt's Method**

If CCA > 0.05 then poor hole cleaning. Else, good hole cleaning and have room to optimize till reach CCA = 0.05

2. **API method**

If CCA > 0.05 then bad hole cleaning. Else, good hole cleaning and have room to optimize till reach CCA = 0.05

3. **Carrying capacity index Method (CCI)**

If CCI < 1 then bad hole cleaning.

If CCI > 1 or equal. Good hole cleaning and have room to optimize till CCI minimum equal 5.

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